# RADIO CHANNEL CAPACITY LIMITATIONS

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The amount of information that can be transferred over any communications link in a unit of time depends upon a number of factors--both technological and physical. This report discusses these factors with emphasis on the fundamental physical limitations of radio channels. The maximum rate of information transfer over a number of radio communication links is derived and compared with an idealized system. The results obtained show that at certain signaling rates, dispersion in the channel, (which is caused by multipath, for example) limits the number of permissible signaling characteristics that can be changed. This may occur even when only two characteristics are used--the minimum number required for information transfer. Thus, dispersive propagation mechanisms limit a binary channel's capacity, and unlike additive noise, this limit cannot be overcome by increasing the signal power.

## 1. INTRODUCTION

There is considerable interest and an increasing need for digital data transmission over military tactical networks. As the demand for higher and higher data rates increases and communications technology advances, the factors which limit this rate tend to shift from technological areas to the fundamental physical limitations inherent in the transmission medium itself.

This report discusses these physical limitations with emphasis on digital systems operating in the microwave region of the spectrum and on links between land-mobile to base-station terminals operating in urban and suburban environments.

The objective of this report is to determine the maximum data rates that can be achieved with some practical systems currently utilizing the radio channel and to present results in a convenient form.

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The report is tutorial in the sense that the presentation is designed for readers who may not be working directly in the radio propagation or radio communications areas but are at least somewhat familiar with the subject. Mathematical equations and derivations have been reduced to an essential minimum. Interested readers can find abundant mathematical details in the numerous references cited in the report. An extensive bibliography on the subject of multipath may be found in Hartman (1974). Additional references on data communications via fading channels may be found in Brayer (1975).

## 1.1 Scope

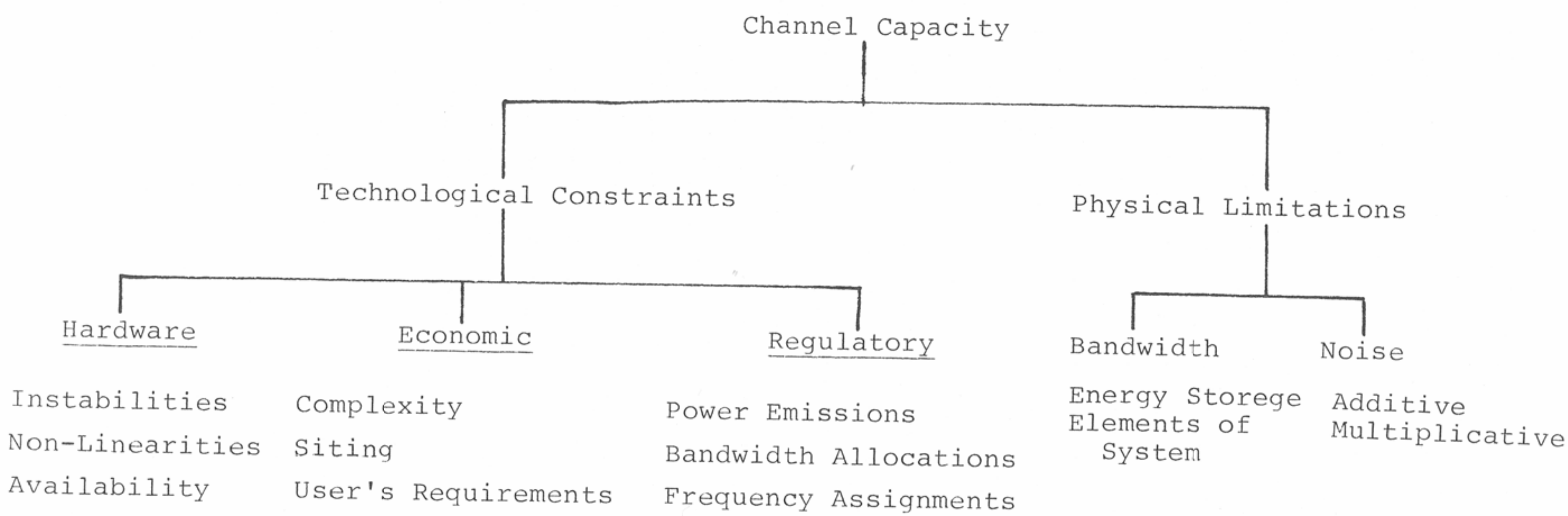
There are several factors which limit the data rate of systems operating over any radio channel. These limitations can be divided into two main categories--technological and physical---as noted by Carlson (1975). The technological problems are soluable in theory but may not be feasible from a practical standpoint. The physical problems, quoting Carlson, "must be faced head-on with no recourse--not even in theory."

Table 1 provides a breakdown of the technological and physical limitations. The technological limitations include hardware, economic, and regulatory constraints. Examples are given in Table 1 under each of these. For instance, hardware availability is a primary limiting factor on system bandwidth. The practical design of antenna systems, band-pass filters and amplifiers with negligible distortion require that the operating frequency range be small relative to the center operating frequency. A rough bound for electronic systems operating anywhere in the radio spectrum is a maximum available bandwidth of about 1% to 10% of the carrier frequency. This implies that the bandwidth could be increased almost indefinitely by going to higher and higher carrier frequencies.

Economic factors evolve from the user's requirements and include such things as system complexity and siting consider-

Table 1

Factors Limiting Capacity of Radio Channels



ations. Regulatory constraints are set by the spectrum management community to maximize utilization of the spectrum resource. For example, power emission and bandwidth allocations along with frequency assignments also have an impact upon hardware design and economics.

The fundamental physical limitations are bandwidth and noise. The bandwidth limits the number of signaling elements or symbols which can be transmitted per unit time. The noise limits the number of distinguishable features on each symbol. The combined effects limit the capacity of a communication system.

It is apparent from Table 1 that a comprehensive review of all the factors limiting channel capacity is an extensive undertaking. Therefore the discussion here is restricted to certain physical limitations. It largely excludes the limitation due to additive noise and interference in the channel. The primary emphasis is on multiplicative noise, i.e., the effects of unpredictable perturbations of the signal by the channel. In many instances results are only qualitative since quantitative measures of pertinent channel characteristics are not available.

The report discusses only certain types of links and transmission channels. Land mobile systems operating in suburban and urban areas are considered quantitatively. However, the factors limiting the data rate on these systems are pertinent to other types of links and channels. Maximum rates achieved with certain other systems have also been estimated and are compared with the mobile systems and an idealized system on a common basis.

## 1.2 Report Structure.

The ultimate goal of the report is to relate radio channel characteristics to the maximum data rate achievable in that channel and to compare these results with an idealized system operating over an undistorted channel against additive noise. This is accomplished by presenting the idealized case first (Section 2). Then the channel characteristics are defined in terms of the channel's effect on the signal (Section 3), the propagation mechanisms which determine the channel's response (Section 4), the mechanisms involved in specific links and their response (Section 5), the response relationship to coherent bandwidth (Section 6), the coherent bandwidth's effect on signaling rate (Section 7), the signal power requirements as a function of signaling rate, (Section 8) and the maximum data rates achieved with undistorted signaling rates (Section 9). Estimates of the maximum rates which can be obtained over various types of links are illustrated (Section 10) and compared with some wideband tactical networks using FM carriers (Section 11). The report is summarized and then, using the results obtained, the principal conclusions are listed (Section 12) and a recommendation is made for additional measurements to confirm these conclusions (Section 13).

## 2. FUNDAMENTAL PHYSICAL LIMITATIONS

The transmission of information, i.e., telecommunications, involves signals or symbols changing with time in a manner which is unpredictable to the recipient. There are two fundamental physical limitations on the amount of information that can be transferred per unit of time. They are <u>bandwidth</u> and <u>noise.</u>

The bandwidth limitation is caused by energy storage elements in the system which prevent instantaneous responses to signal changes. The noise limitation prevents the system from distinguishing between differences in the symbols by constraining the number of information bits that can be conveyed by each symbol with an acceptable error rate.

Symbols changing with time determine the signaling rate. The number of distinguishable symbols available determines their information content. A minimum of at least two is required to transfer information. If the signaling rate is $1/\tau$ symbols per second and there are H information bits per symbol, then the received data rate, R is given by

$$R = \frac{H}{\tau} \quad \text{b/s.} \tag{2-1}$$

If there are m distinguishable and equally probable symbols at some acceptable error rate, then, by definition, the information content is

$$H = \log_2 m \text{ b/symbol.} \tag{2-2}$$

For binary systems, m=2, and there is 1 bit/symbol.

The signaling rate is inversely related to the bandwidth. For an ideal filter whose amplitude vs. frequency response is constant over a bandwidth B, the maximum signaling rate is given by Nyquist, (1928), assuming no intersymbol interference as

$$\frac{1}{\tau} = 2B \quad \text{symbols/s.} \tag{2-3}$$

This Nyquist restriction applies only to the symbol or baud rate - not the data rate in b/s. For this condition, the maximum data rate is

$$R = 2B \log_2 M \tag{2-4}$$

The maximum number of symbols m which can be distinguished with arbitrarily low error probability in additive Gaussian noise was shown by Shannon (1948) to be

$$m = \left(1 + \frac{S}{N_o B}\right)^{1/2}, \tag{2-5}$$

where S is the average received signal power, with no restriction on signal shape or duration, $N_o$ is the noise power spectral density and B is the ideal filter bandwidth.

The capacity of this idealized channel thus becomes

$$\begin{aligned} R \le C &= 2B \log_2 \left(1 + \frac{S}{N_o B}\right)^{1/2} \\ &= B \log_2 \left(1 + \frac{S}{N_o B}\right) \end{aligned} \quad \text{b/s.} \tag{2-6}$$

Unfortunately, the existence proof for this upper bound on the information rate provides no insight into the signal encoding process. Also there are very few instances of real communication channels where Equation 2-6 applies.

The actual data rate can only approach the channel capacity using an extremely complicated encoder. The statistical properties of the signal approach those of Gaussian noise and the coding time increases indefinitely.

Rice (1950) has shown that in order to achieve a data rate which is 96 percent of the channel capacity with $S/N_oB = 10$ and an error probability of $10^{-5}$ the number of block encoded channel signals required is $2^{10,000}$. This is just as impractical as the infinite coding delay required.

An upper bound for the average probability of error, $P_e$, can be written in the form

$$P_e \leq 2^{-T_s E(R_c)} \tag{2-7}$$

for random codes where the signals are constrained only in average power and bandwidth. $T_S$ is the signal duration and $E(R_c)$ is called the error exponent. An exact expression for $E(R_c)$ is extremely complicated. In the limiting case where $T \rightarrow \infty$ and the channel has unity gain over a bandwidth B then the $E(R_c)$ expression is simplified to the expression for capacity given by Equation (2-6). Thus, the capacity is the highest rate where the error exponent is positive.

Equation (2-7) shows that the upper bound of the average error rate decreases exponentially with increasing signal duration, $T_s$. Even when more practical (from an implementation standpoint) digital signals are used with distinguishable levels constrained to be relatively small and with codes composed of sequences of such signals, the exponential decrease in error rate with code length is retained, but at a lower rate and the capacity is reduced.

The capacity equation (2-6) can be solved for a lower bound on S, thus

$$S = \left(2^{C/B} - 1\right) N_o B \text{ watts.} \tag{2-8}$$

In terms of decibels (dB) relative to one watt

$$10 \log_{10} S = 10 \log_{10} \left(2^{C/B} - 1\right) B N_o \text{ dBW.} \tag{2-9}$$

The noise power spectral density is given by

$$N_o = kT = 4x10^{-21} \text{ watts/Hz}, \qquad (2\text{-}10)$$

where k=1.38 x $10^{23}$ joules per degree Kelvin is Boltzmann's constant, and T = 290 degrees Kelvin, a typical temperature seen by a radio system's antenna.

Thus,

$$10 \log_{10} N_o = -204 \text{ dB}, \qquad (2\text{-}11)$$

and the average receive signaling power becomes

$$10 \log_{10} S = 10 \log_{10} \left(2^{C/B} - 1\right) B - 204 \text{ dB}. \qquad (2\text{-}12)$$

A plot of the capacity, C, versus bandwidth, B, and parametric in signal power in decibels (dB) is shown in Figure 1. Curves parametric in C/B are shown on the same figure to indicate the importance of this parameter. Note that when B = 1/τ the parameter C/B is the same as the information content, H.

It is apparent in Figure 1 that for a fixed power and noise more and more efficient communication is possible with an idealized system, as the bandwidth is increased. With no bandwidth limitation the signal-to-noise ratio per information bit, $S/N_oR$, approaches a limit of $\ell n2 \approx 0.69$ or -1.6 dB as noted by the horizontal slope of the curves for constant S. Although this limit is reached only for infinite bandwidth, it is within about 1 dB when the packing ratio R/B = 0.5 b/s/Hz. In the power limited region where R is directly proportional in S coding, techniques provide a means of reducing power or increasing the data rate. Forney (1970) shows some of the potential gains achievable with various practical coding schemes. For example, the simplest possible sequential decoder working with rate 1/2 codes, phase shift keying, and making hard decisions has a theoretical limit of $S/N_oR$ = 4.5 dB for essentially zero error probability. This can be compared with the -1.6 dB ideal limit. The theoretical limit of any sequential decoder on a white Gaussian channel accounts for 3 dB of this loss. An additional 2 dB loss is due to the

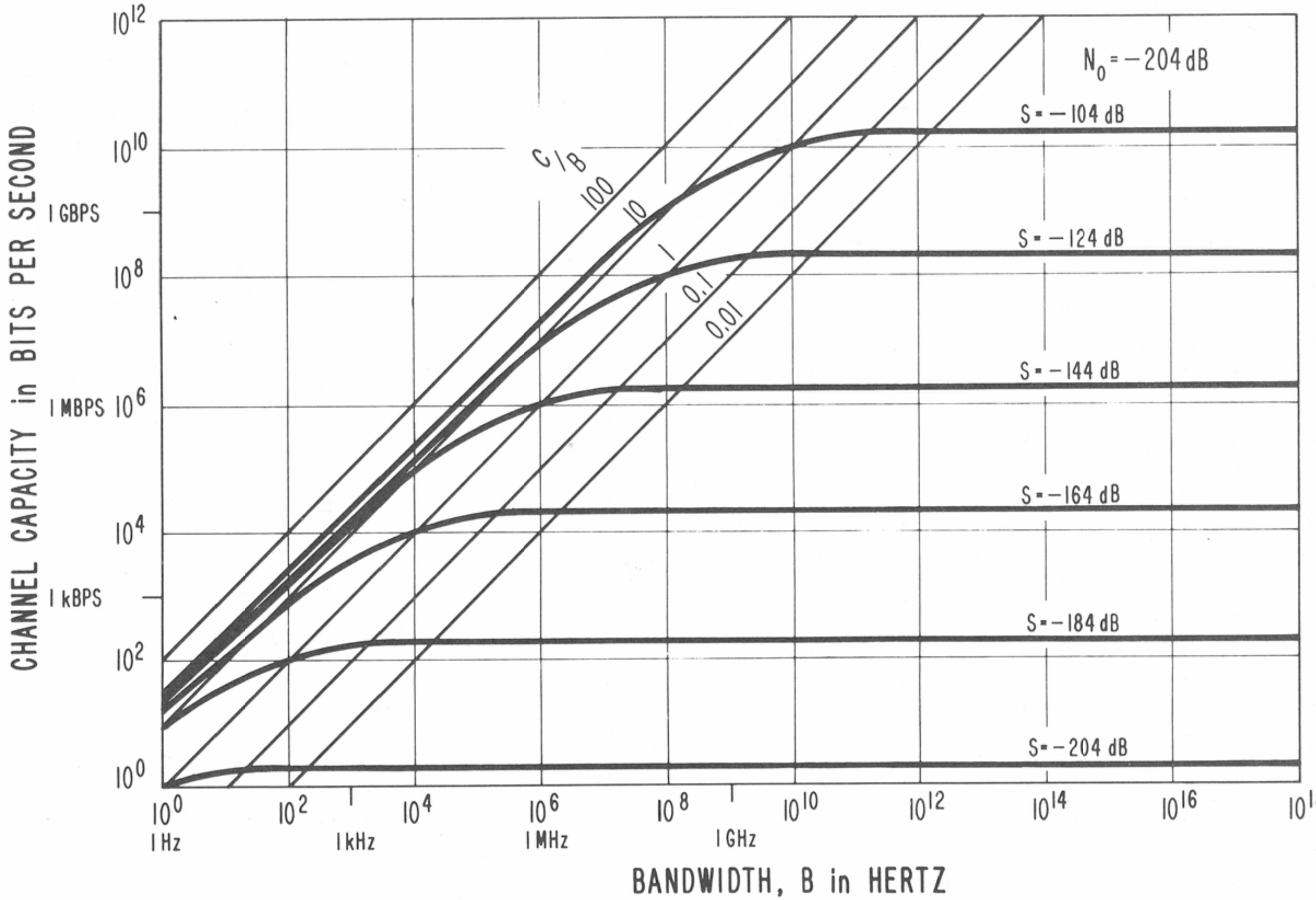



Figure 1. Channel capacity of idealized system versus bandwidth parametric in average received signal power, S in dB for constant noise power spectral density, $N_O$ (dark lines) and parametric in packing ratio, C/B (light lines).

hard decisions and 1 dB to the choice of rate 1/2 rather than some lower rate.

Measured performance data obtained with one high speed sequential decoder are shown by Forney (1970) to be within 1 dB of the expected theoretical limit at $P_e = 10^{-5}$ for the sequential decoded PSK system.

When the channel is bandwidth limited rather than power limited the channel capacity can be approached without coding by increasing the number of distinguishable levels, i.e., the packing ratio.

The curves in Figure 1 are replotted in Figure 2 to show idealized capacity as a function of signal power level and parametric in packing ratio. This plotting format is used repeatedly in Section 8 of this report to show the effect of modulation, channel distortion, and diversity reception on the signaling ratio achievable with some practical uncoded systems.

The bounds on error probability given by Equation 2-7 and other similar expressions involving constraints on signal design are often used as standards against which actual systems can be measured. In this report, however, the ideal (Shannon) limit on capacity is used to illustrate a common, though unachievable, upper bound on data rate.

## 2.1 Practical Considerations

Shannon's channel capacity expression (eq. 2-6) provides an upper bound for error free transmission in a linear baseband channel. Radio channels require that this baseband be converted to a passband at radio frequencies. This involves modulation of a carrier so that the modulation envelope follows the baseband signal. Although a digital system may be considered wideband in terms of data rate, the radio signals are actually, narrowband relative to the carrier frequency in order to define this envelope.

Since radio channels are basically analog channels some form of modulation and demodulation (modem) is required to match digital baseband signals to the transmission medium. This

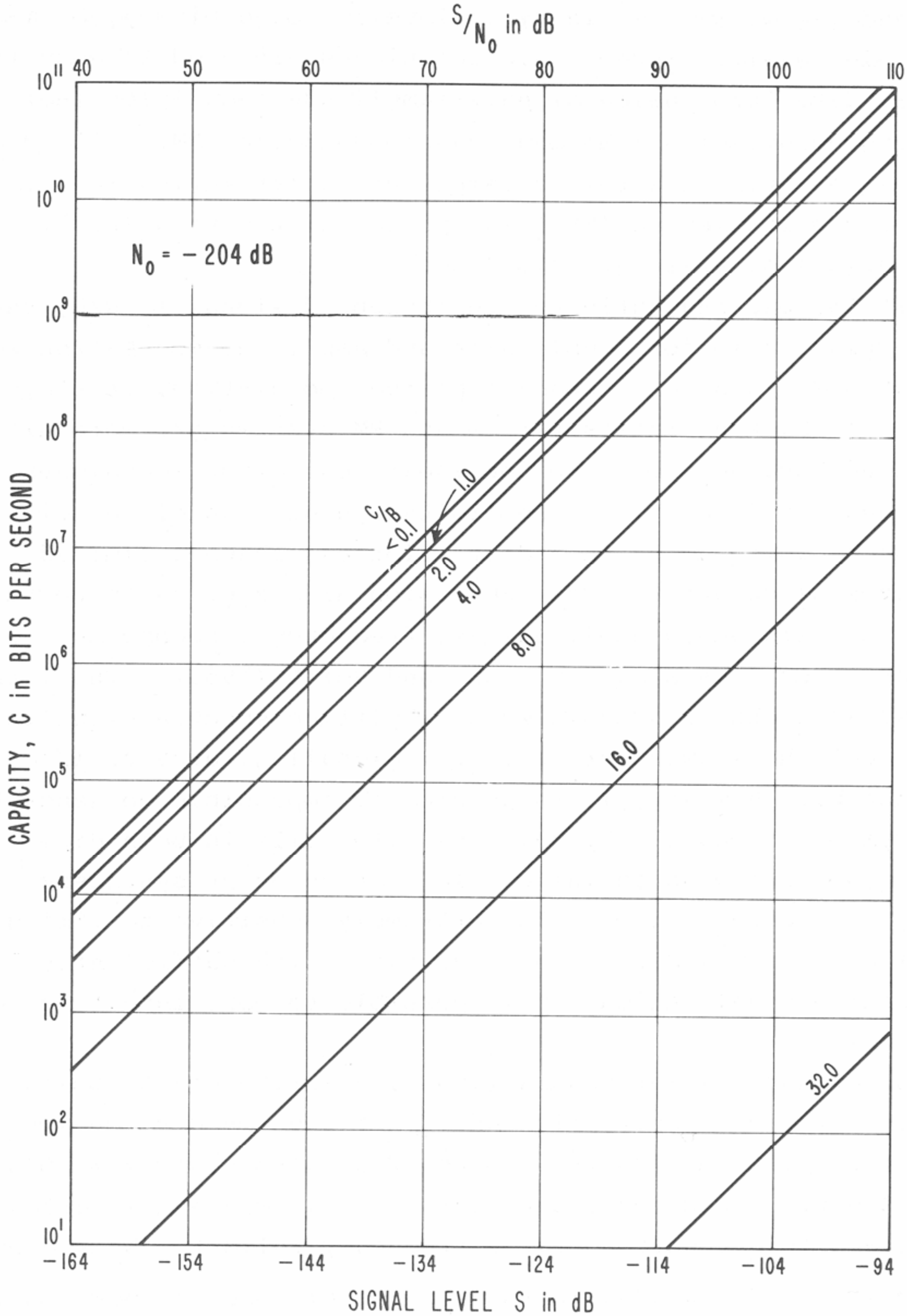



Figure 2. Channel capacity for ideal system. B is the channel bandwidth.

baseband signal may be binary (2 level), coded binary, or m-ary (multiple level). Three basic techniques are used to convert the digital data into analog signals--amplitude modulation (AM), frequency modulation (FM) and phase modulation (PM). For digital systems they take the form of amplitude shift keying (ASK), frequency shift keying (FSK) and phase shift keying (PSK). Combinations of these are also used.

If the packing ratio for the baseband signal is R/B, then the packing ratio for double sideband amplitude modulation would be R/2B. For single sideband amplitude modulation, it stays the same. The packing ratios for FM and PM systems are more difficult to define because these are nonlinear modulation techniques.

Equation (2-6) gives the limitation on channel capacity imposed by white noise in a distortionless channel limited to an idealized bandwidth B. The expression also applies to certain other channels whose amplitude vs. frequency response may not be constant over B as shown by Gibby and Smith (1965). This, then, is a whole class of symbols whose amplitude spectra with linear phase meet the Nyquist criteria for signaling rates of $1/\tau = 2B$. In principle, however, it is physically impossible to generate such symbols because they have infinite tails in both directions and would require an infinite delay for an exact synthesis. The slowly decreasing tail is also extremely sensitive to timing errors and channel distortion. However, with sufficiently complicated equalization, it is possible to make interference very small.

Lucky and his colleagues (1968), describe one symbol with raised cosine characteristics which has been used extensively. The total spectrum occupies a bandwidth $B_T=kB$ where k is greater than 1 and is a function of the frequency rolloff. As k decreases, $B_T$ is less and response in the time domain becomes more oscillatory approaching the ideal response which has the form $\frac{\sin x}{x}$.

However, the problems of timing and channel equalization become more difficult. A typical value used is k=2, and the signaling rate in terms of the total bandwidth $B_T$ becomes

$$\frac{1}{\tau} = B_T \qquad (2\text{-}13)$$

The data rate then is given by

$$R \le \frac{B_T}{2}\log_2\left(1+\frac{S}{N_o B}\right), \qquad (2\text{-}14)$$

and the average received signal power is thus obtained from

$$\text{S (raised cosine)} = \left(2^{2R/B_T}-1\right)BN_o$$

$$= \left(2^{R/B_T}-1\right)\left(\frac{2^{R/B_T}+1}{2}\right)BN_o\,. \qquad (2\text{-}15)$$

The signal power required for the idealized system was previously found to be (Equation 2-7),

$$\text{S (idealized)} = \left(2^{R/B}-1\right)BN_o\,. \qquad (2\text{-}16)$$

In order to obtain identical data rates and occupied bandwidths with either system so that $R/B = R/B_T$, the raised cosine system requires additional signal power by an amount in dB qiven by

$$10\log_{10}\frac{S(raised\cos ine)}{S(ideal)} = 10\log\left(\frac{2^{R/B}+1}{2}\right). \qquad (2\text{-}17)$$

For R/B = 2,,4, and 8 bits/s/Hz, this amounts to 4 dB, 9.3 dB, and 21 dB, respectively.

Two other factors tend to limit the data rate. One is the variations in signal level (power fading) which are caused by the channel but do not distort the signaling element or cause inter-symbol interference. In this case (defined as flat-flat channel in Section 3), it is necessary to find the average signal power by averaging over some fade distribution x. Various distributions have been used depending on the channel involved.

When a large number of multipath components exist without any major components as in some urban mobile links, the fading approximates a Rayleigh distribution. Other distributions are described in the literature. For example, see Nesenbergs (1967).

The other factor limiting data rate is multiplicative noise which is introduced by random distortions in the channel. Predictable amplitude and phase variations in channel can be corrected, at least in principle. Complete elimination, however, is difficult in practice and the remaining variations differ between similar links and in time on the same link in a random manner.

Under these conditions, the data rate has an upper bound given by

$$R < \frac{B_T}{2} \log 2\left(1 + \frac{SX}{DS + N_o B}\right) \qquad (2\text{-}18)$$

where the symbol X reflects the non-distorting, flat-flat power fading of S and where DS is the noise due to random distortion in the channel. A similar expression is given by Sunde (1954) for wired systems where X = 1.

The distortion factor D is the result of unpredictable amplitude fluctuations and phase deviations in the channel. It is apparent that the multiplicative noise term DS places a limitation on data rate which unlike the additive noise term N B or the flat-flat fading cannot be overcome by increasing the signal power.

The impact of these factors on the reliability or error rate of some uncoded systems in use today is illustrated in Figure 3. The error rates for several binary systems operating in additive white noise are bounded within the shaded curves. Numerous examples of specific curves of this type may be found in the literature. For three such examples see Schwartz, et al., (1966), Bello and Erhman (1969), and Frasco and Goldfein (1973).

Curves are plotted in Figure 3 for a non-fading channel, a Rayleigh fading channel, and a selective fading channel. The width of the curves bounds the performance between several modulation schemes including phase shifted keying (PSK) on the left and noncoherent frequency shift keying (FSK) on the right. Other systems whose performance falls within these bounds include

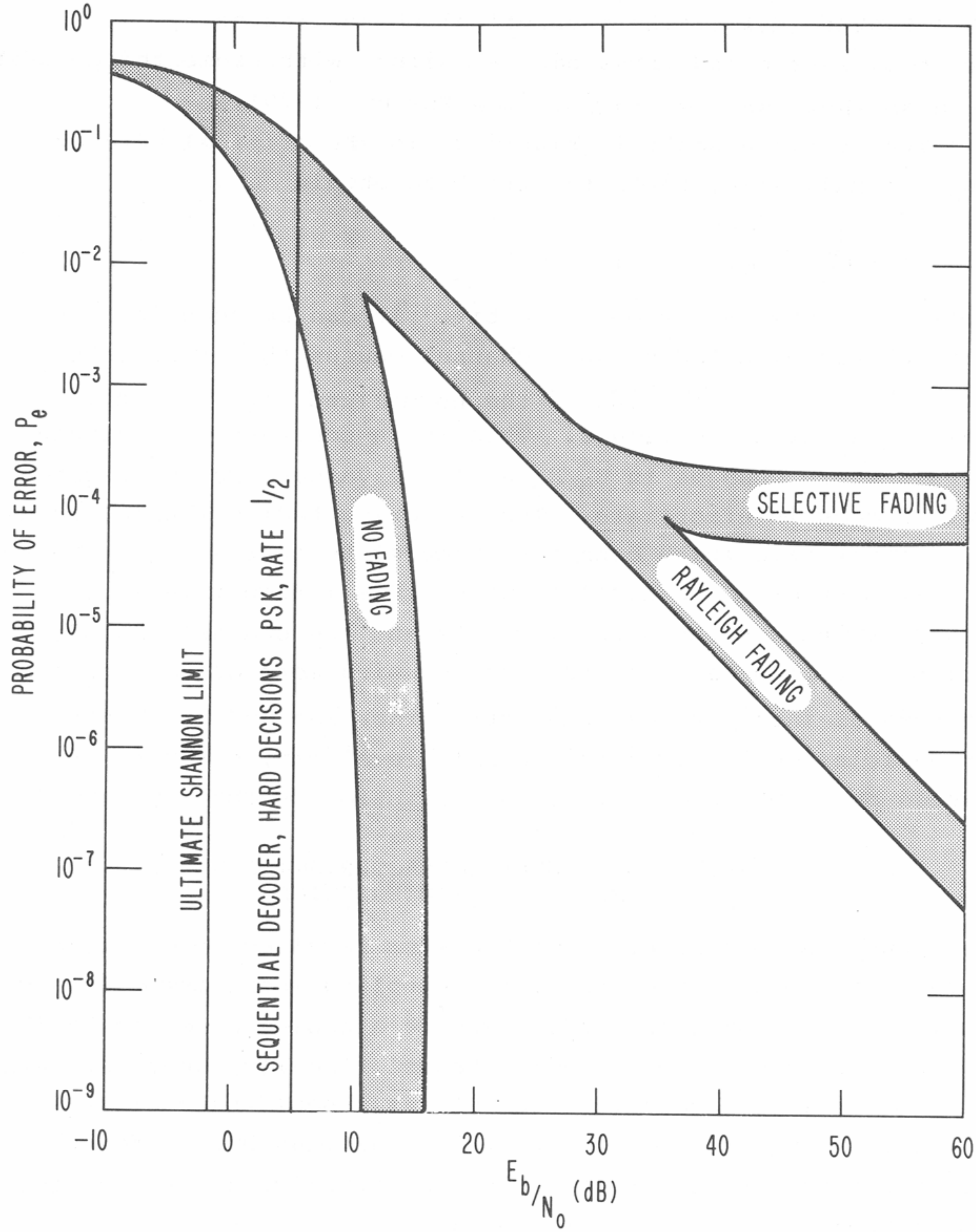



Figure 3. Uncoded binary system error rate as a function of signal-to-noise ratio per information bit.

coherent FSK, differentiated PSK, quadrature PSK, and minimum shift keying (MSK). The theoretical channel capacity limits for the ideal system and for a digital signal with segmented decoding are also shown on the figure. See Forney (1970).

The abscissa scale in Figure 3, is the critical parameter $S/N_o$, normalized by the data rate R to obtain

$$\frac{S}{RN_o} = \frac{E_b}{N_o} \qquad (2\text{-}19)$$

where $E_b$ is the energy per data bit. It can be seen in Figure 3 that the Rayleigh fading on a channel causes the error rate to vary in inverse proportion to the normalized signal-to-noise ratio $E_b/N_o$ at large values. This is in contrast to nonfading signals where changes in $E_b/N_o$ at large values produce exponential changes in error rate. The selective fading channel results in an error rate which cannot be reduced by increasing $E_b/N_o$ for certain systems. The level at which this irreducible error rate occurs depends on the signaling rate and the channel characteristics. As this rate is increased causing more distortion or intersymbol interference, the errors increase and raise the irreducible level. This irreducible level can, however, be reduced by adaptive equalization prediction feedback or coding.

## 3. RELATING CHANNEL CHARACTERISTICS TO SIGNALING CHARACTERISTICS

Long-distance information transfer requires some form of transmission medium and associated coupling mechanism or transducer. The transmission medium may be a cable, an optical fiber, an acoustic channel, or a radio channel. Ideally, whatever method is used the information transfer process should take place with no error. However, the outputs from real channels differ from the inputs because the transfer characteristics are not perfect and because of the omnipresent noise.

This report is concerned with terrestrial radio channels where the information transfer is accomplished by electromagnetic propagation through the atmosphere, at least on some portion of the path. Terrestrial radio channels tend to be dispersive by nature distorting multifrequency signaling wave forms in unusual and everchanging ways. The dispersive character of radio channels takes two independent forms: time dispersion and frequency dispersion. Time dispersion is manifested in the time domain by the spreading or smearing of pulses of short duration when they are propagated through the medium. Frequency dispersion is manifested in the frequency domain by the spreading or shifting of the frequency spectrum of narrow-band signals. Time and frequency dispersion may cause signals to fade in time, they may distort the symbols, or they may produce intersymbol interference. The following subsections describe the dispersive effects of the radio chaunel on the signal. The definitions used are essentially those given by Kennedy (1969).

## 3.1 Time Dispersion

Time dispersive effects fall into two causitive classes, those due to the frequency dependence of atmospheric effects upon propagation paths and those due to mechanisms producing multiple propagation paths, i.e., multipath.

In the first class, frequency dependence results from the complex refractive index of rain, water vapor and oxygen in the atmosphere. Broadband signals may be distorted when the amplitude of the channel transfer function varies with frequency or its phase varies nonlinearly with frequency.

In the second class, multipath results when the signals propagated along different path lengths arrive at their destination with different time delays. The resulting multipath spread causes frequency-selective fading which introduces signal distortion and, when severe, causes intersymbol interference.

Time-dispersion characteristics are determined by measuring the delay power spectrum (or impulse response) of the channel. A useful measure of the frequency selectivity is the coherence bandwidth. It is obtained by Fourier transform of the impulse response to give the frequency autocorrelation function.

Coherence bandwidth is then defined as the frequency separation where the autocorrelation function falls below some specified value. Time dispersive effects tend to limit the maximum useable signaling rate (Bello and Nelin, 1964).

## 3.2 Frequency Dispersion

Frequency dispersion is caused by time variations in the propagation path due to changes in the medium itself, terminal motion, or combinations of these. These dynamic changes in the channel can cause signals to fade and, when severe, cause time-selective fading.

Frequency-dispersion characteristics are determined by measuring the frequency power spectrum of the channel. A useful measure of the time selectivity is the coherence time. It is obtained by doing a Fourier transform of the frequency power spectrum to give the time autocorrelation function. Coherence time is then defined as the time separation where the autocorrelation function falls below some specified value. Frequency dispersion effects tend to limit the minimum useable signaling rate (Bello and Nelin, 1964).

## 3.3 Channel Classifications

Time and frequency dispersion are independent measures of channel characteristics. A channel may be considered as non-disperslve, dispersive in time, dispersive in frequency or dispersive in time and frequency, depending on signal characteristics. Although all radio channels are dispersive to some extent, their distortive effect on transmission of signals depends on the magnitude and type of dispersion relative to the duration of signaling symbols and relative to signal bandwidth. If the symbol duration is long compared to the time dispersion, distortion is negligible. All frequency components of the signal fade together. This is called non-frequency selective fading or a time flat channel. As the symbol duration decreases, frequency components fade independently, the symbol is distorted and the channel becomes frequency selective.

When the bandwidth of the signal is wide compared to the frequency dispersion, the distortion is negligible. The amplitude and phase of a complete symbol or several symbols may still vary with time. This is called non-time selective fading or a frequency-flat channel. As the bandwidth of the signaling element decreases the amplitude and phase may vary over a single symbol causing distortion and the channel becomes tune selective.

A radio transmission channel with a given set of time and frequency dispersive characteristics may be called by different names depending on the signal format employed. When the signal is undistorted the channel is neither time selective nor frequency selective. This is called the time-flat and frequency-flat channel or just a flat-flat channel. Note that amplitude and phase of the symbols may vary slowly with time relative to the signaling speed.

Table 2 summarizes the effects of the channel on a signal, wherein signal distortion and intersymbol interference effects have been lumped together.

## 4. RELATING CHANNEL CHARACTERISTICS TO DISPERSIVE MECHANISMS

Some of the various propagation mechanisms involved in a microwave radio channel are illustrated in Figure 4. Signals arrive at the receive terminal via direct, refracted and reflected paths where they combine to form a composite signal (Dougherty, 1968). The paths are different lengths and change with time. Along each path wideband signals are also perturbed by the dispersive nature of the medium as the complex index of refraction varies with frequency. They may also be perturbed by scattering from turbulent inhomogeneities in the atmosphere. Ideally, a system designer would prefer to use only one of these paths (the direct one in the situation depicted), but it is difficult to excite and resolve only one.

The propagation mechanisms illustrated in Figure 4 are represented by blocks in Figure 5. Although there is usually

Table 2

Classifications Derived From Effects of the Channel on the Signal

| Channel Descriptor | | Non Dispersive | Dispersive In Time | Dispersive In Freq. | Doubly Dispersive |
|---|---|---|---|---|---|
| Effect on Signal | | No Distortion | Frequency Distortion | Time Distortion | Time and freq. Distortion |
| Fading Characteristics | | Time Flat Frequency Flat | Time Flat Frequency Selective | Frequency Flat Time Selective | Time Selective Frequency Selective |
| Signal Characteristics | Band-width | Much Less Than Coherence Bandwidth | Greater Than Coherence Bandwidth | Less Than Coherence Bandwidth | Greater Than Coherence Bandwidth |
| | Duration | Much Less Than Coherence Time | Less Than Coherence Time | Greater Than Coherence Time | Greater Than Coherence Time |

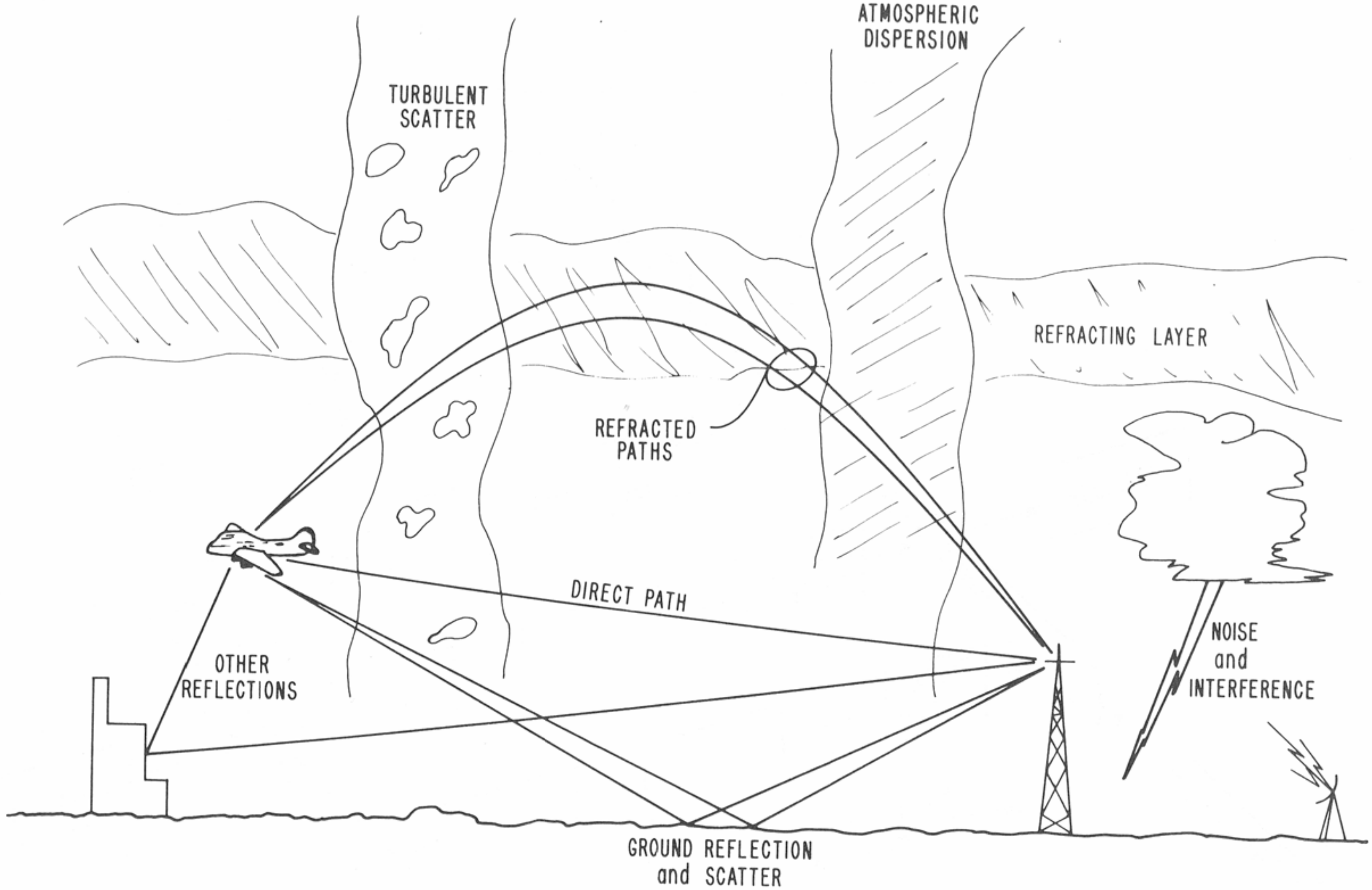



Figure 4. Dispersive mechanisms in a channel.

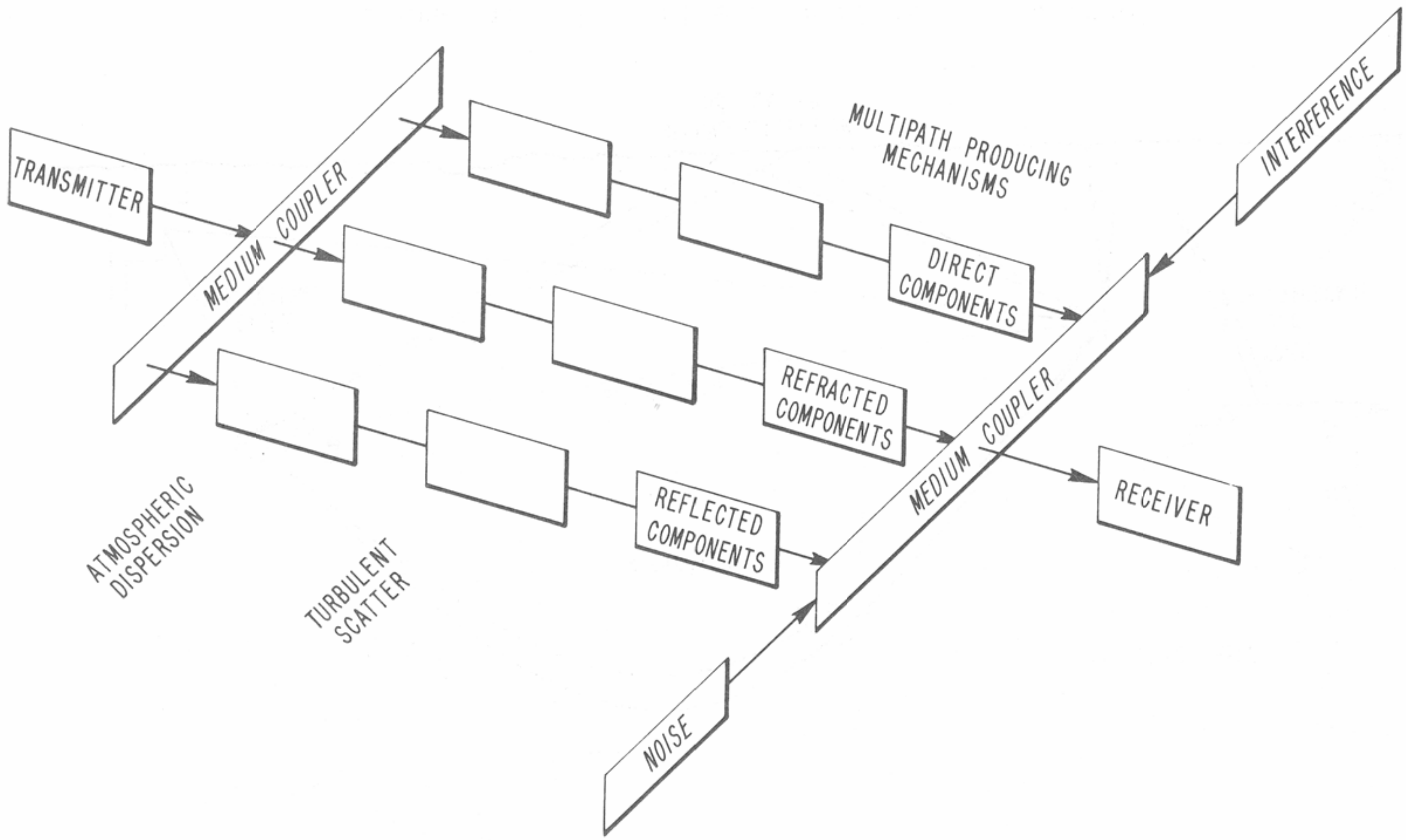



Figure 5. The radio channel.

only one direct path (which may be diffracted) there may be additional refracted paths (usually only 1 or 2) and several reflected paths.  The presence or absence of any path depends on link geometry, the operating environment, meteorological conditions and geographical location.  Sometimes a particular propagating mechanism is desired and sometimes it exists when not wanted.  For example, ionospheric refraction is used for long distance links in the HF band.

Interference from refracted paths may occur on microwave line-of-sight links at low grazing angles when layering in the atmosphere causes variations in the refractive index.

Reflected waves and additional refracted paths may be absent entirely on some links--a ground-to-satellite link, for example. Even the direct path can fade or not even exist.  It may be blocked by an obstruction such as a building in the path of a mobile unit to a base station.

Reflected, refracted, diffracted, and direct paths may all be non-existent, e.g., transhorizon links use scatter mechanisms only--either ionospheric scatter or tropospheric scatter.  In this case, the dispersive mechanisms are limited to medium dispersion and turbulent scatter.

The medium couplers depicted in Figure 5 are the transmit and receive antenna systems.  Directive antennas may be employed to reduce the multipath dispersion by discriminating against reflected components.  Narrow beamwidths tend to reduce the time spread due to scattering mechanisms.  Multiple coupling antenna configurations are often used to provide space diversity to improve performance on fading channels.

Table 3 lists the gross characteristics for some microwave channels.  The estimates given are only approximate and were obtained from a variety of sources.  Pertinent sources are listed later in Section 10 in Table 9.  The values listed here for the delay spread of the dispersive medium and turbulent scatter mechanisms are rms values of the delay profile.  The delay indicated for refracted and reflected components is the maximum delay

Table 3

Gross Channel Characteristics for Microwave Channels

| Channel Characteristic | Delay Spread | Time Variability |
|---|---|---|
| Medium Dispersion | | |
| • Clear Sky | <0.1 ns | Diurnal & Seasonal |
| • Heavy rainfall | <0.2 ns | Minutes to hours |
| Turbulent Scatter | | |
| • Atmosphere (non-ionized) | <1.0 ns | Seconds |
| • Troposcatter | <1.0 μs | Seconds to Minutes |
| • Ionospheric | <100 ns | Seconds |
| Refraction | | |
| • Fixed Terminals | <10 ns | Minutes to hours |
| • Moving Terminals | <10 ns | Seconds to minutes |
| Reflection | | |
| • LOS Links | | |
| Grid to Grid | <10 ns | Hours |
| Air to Grid Link | <10 ns | Minutes |
| Air to space | <10 ns | Minutes |
| • Mobile links | | |
| Urban | <5 μs | Seconds |
| Suburban | <0.5 μs | Seconds |

relative to a direct path. The time variability indicates typical values for the periods of time over which the channels' characteristic parameters can no longer be considered stationary.

Diffractive effects have been neglected here although they can have considerable impact on the observed channel response because the strength of various components can change due to diffraction. In the mobile environment the signals at shorter delays may be enhanced at lower frequencies due to diffraction around obstructions. See Turin, et al., (1972).

## 5. RELATING PROPAGATION MECHANISMS TO CHANNEL RESPONSE OF SPECIFIC LINKS

This section indicates some qualitative response functions obtained on certain specific links and quantitative response functions for mobile links. Here, emphasis is on the impulse response rather than on the frequency transfer function of the channel. Either would suffice since one is the Fourier transform of the other. Generally, the impulse response is easier to relate to the physical characteristics of the channel. The square of the absolute value of the response is sometimes called the delay power spectrum or multipath profile. It is a measure of the received signal power distribution in the time domain.

An instantaneous impulse response is obtained when the channel is excited by an impulse whose duration is much less than the dispersive character to be measured. Since the response usually changes slowly with time and space, an average of many instantaneous responses may be used to describe the actual response as a statistical representation of the channel over short periods and distances. The time variability of the response over longer periods and distances defines the rapidity of fading due to the dynamics of the path.

Some delay power spectra averaged over short periods are illustrated qualitatively in Figure 6 for certain representative links. The variability with type of link is clearly indicated. Although the detailed characteristics of a given type of link will vary, the general characteristics tends to remain the same

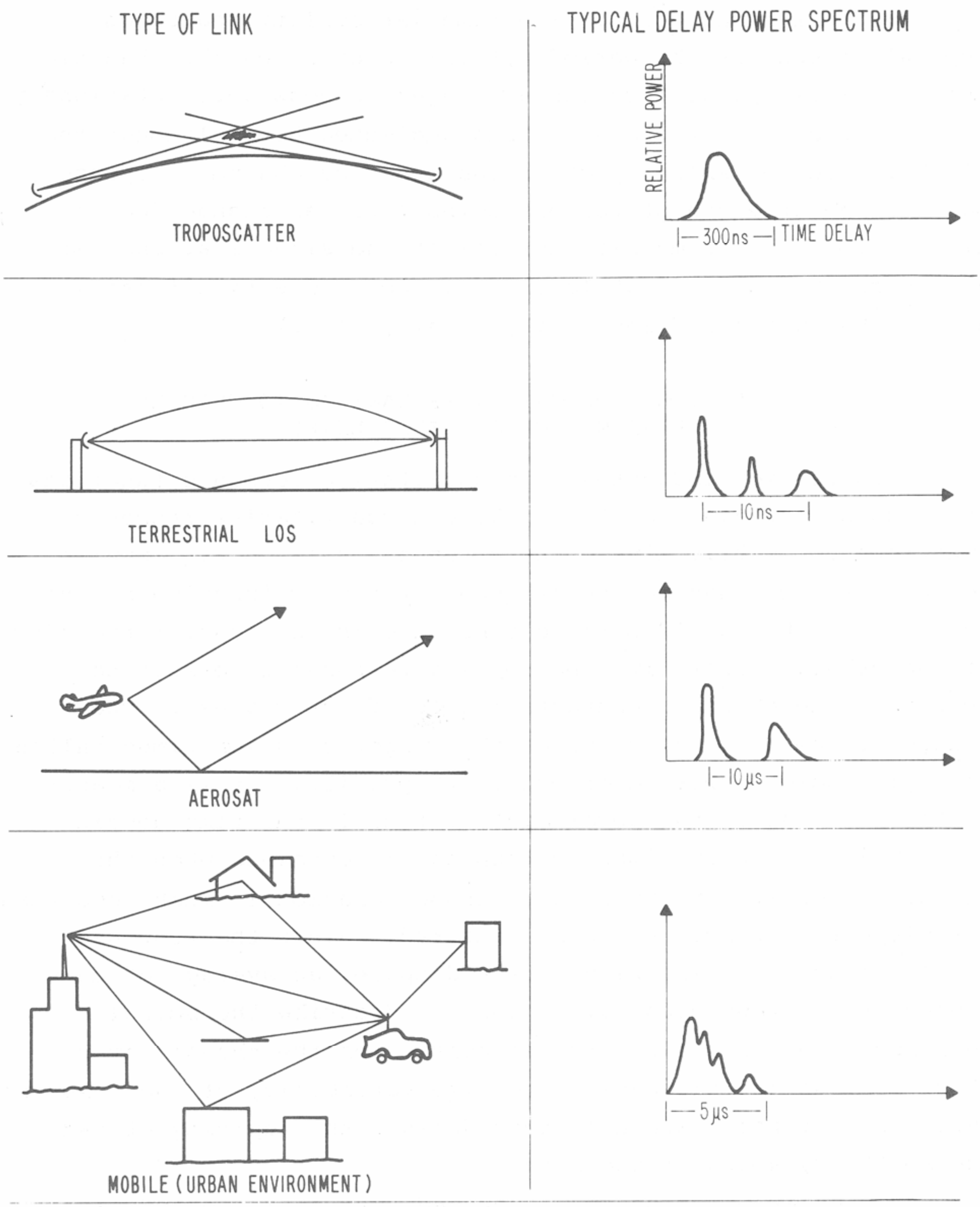



Figure 6. Relating delay power spectrum to specific links.

This variation depends on many factors including range, geographic location, carrier frequency, meteorological conditions, link geometry, terminal motion, antenna height, beamwidth, and pointing angle.

For any specific link, the general character of the response depends on the propagation mechanisms involved. Table 4 indicates this relationship for representative links.

There are numerous methods used to describe a delay profile. A gross description is obtained from approximating the total width including all discrete components falling above the background noise threshold. Some typical values are given on the responses in Figure 6.

A more quantitative single number representative of the time delay is the rms spread, $S_d$, given by the square root of the second moment. For example, see Cox (1972a).

$$S_d = \left[ \sum_{k=1}^{m} (\tau_k - \tau_o)^2 P_k \Big/ \sum_{k=1}^{m} P_k \right]^{1/2} \tag{5-1}$$

where the mean path delay is given by the first moment with respect to the first arrival delay, $\tau_a$, i.e.,

$$\tau_o = \sum_{k=1}^{m} \tau_k P_R \Big/ \sum_{k=1}^{m} P_R - \tau_a \tag{5-2}$$

The summations from k=l to m include an arbitrary delay before the minimum arrival delay $\tau_a$ where the profile amplitude is insignificant and a sample at m corresponding to the last delay of significant amplitude. Other measures of width used by Cox (1972a) include the delay between the outer -3 dB or -10 dB points.

A fairly complete discussion and presentation of descriptors is given by Nielson (1975) for profiles obtained over mobile links. In addition to those given above, these include the

Table 4

Relating Propagation Mechanisms to Specific Links

| Propagation Mechanism / Specific Link | Medium | Scattered | | | | Reflected | | Refracted | | Direct |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Atmo-sphere | Earth's Surface | Tropo-sphere | Iono-sphere | Earth's Surface | Other Objects | Tropo-sphere | Iono-sphere | |
| Transhorizon HF Skywave | U | U | | | | | | | P | |
| Ionoscatter | U | U | | | P | | | | | |
| Troposcatter | U | U | | P | | | | | | |
| Terrestial LOS | U | U | S | | | S | | S | | P |
| Mobile | U | U | S | | | S | S(D) | | | P |
| Aeronautical | U | U | S | | | S | | S | | P |
| Satellite | U | U | S | | U | S | | | | P |

P = Preferred
S = Sometimes Present

U = Unavoidable
S(D) = Alternate Preferred

number of resolvable components, distribution of delays between resolvable components, and the rms-to-average ratio of the profile amplitude. Nielson also indicates that the delay spread parameter, $S_d$, does not adequately describe profiles containing discrete, closely spaced components.

Mathematical functions which approximate the shape of a given profile are often found in the literature. See Gans (1972). Examples include Gaussian, exponential, rectangular, and discrete-valued functions. Representing different channels in this manner permits the subsequent mathematical manipulations (Fourier transforms, for example) to become more tractable. The Gaussian function is often used to describe the received process when multiple paths cannot be distinguished physically. This is often the case when scattering mechanisms are involved and the number of scatterers is fairly large.

Hartman (1974) has collected together many of the theories and techniques used in solving multipath problems including the classification of multipath and its effect on systems. He indicates, for example, how to treat a two-discrete-paths model when the statistics enter the problem only through the probability that a particular delay will occur.

## 5.1 Time Dispersion in Mobile Links

Land-mobile links are commonly used for short-range communications distances up to about 30 km. Portions of the VHF and UHF frequency bands have been allocated for this purpose.

The multipath characteristics for mobile links operating in urban and suburban environments have been measured by various groups. One readily measured characteristic is the amplitude variation of the envelope of a signal transmitted over a mobile link as the terminal position is changed. Several workers have made such recordings at frequencies ranging from 50 MHz to 12 GHz. A mathematical theory and review is given by Clark (1968). Over short distances the fading envelope tends to be Rayleigh distributed indicating the resultant field consists of a number of reflected waves with random amplitudes and angles of arrival and uniformly distributed phases. When there is a significant direct path signal, the envelope tends to be Rice distributed.

At longer distances, the fading tends to approach a log-normal distribution because of the terrain and the effects of other obstacles. These characteristics are important for evaluating the performance of systems when the signaling rate corresponds to a time-flat, frequency-flat channel. For selective channels, the time and frequency spread are of interest. These have also been measured using different techniques and at different frequencies. The general scheme for measuring delay spread is to transmit short pulses and observe the echoes. Pseudo-random (PN) codes are also used. When keyed at high rates, such codes can be cross correlated with an identical code at the receiver, yielding short impulse functions. The width of the pulse in either case determines the system resolution capability. Table 5 summarizes the characteristics of systems used by various workers.

The reflected and scattered signals arriving at the measuring terminal will be frequency (Doppler) shifted by an amount depending on terminal velocity and the angle of arrival relative to the terminal's velocity vector. These frequency shifts can be measured with the PN code equipment when quadrature coherent detection is used and stable frequency references are available. See Cox (1973).

Different workers used different methods to analyze their results. Young and Lacy (1950) made tests at 450 MHz in the lower part of Manhattan in New York City. Pulse profiles are presented as sequences of motion-picture frames along several streets. Their statistical analysis shows the data in a form of probability that minor paths will appear within specified intervals of relative delay. The maximum time delay spread is about 5 microseconds with an approximately exponential distribution.

Table 5

Mobile Channel Response Measuring Systems

| Reference | Carrier Frequency | Measurement Range | Signal Character | Resolution (Pulse Width) |
|---|---|---|---|---|
| Young and Lacy (1950) | 450 MHz | ≤10km | Pulse | 500 ns |
| Turin, et al.(1972) | 488, 1280, 2920 MHz | 1.6km to 8.8km | Pulse | 100 ns |
| Cox (1972a, 1972b, 1973) | 910 MHz | 4km to 5km | PN Code | 100 ns |
| Nielson (1975) | 1370 MHz | <20km | PN Code | 100 ns & 50 ns |
| Linfield, et al.(1976) | 8600 MHz | 1 to 10 km | PN Code | 6 ns |

Turin and his colleagues (1972) report multipath spread measurements in the East Bay region of the San Francisco Bay area and in San Francisco itself. Observations were made at three frequencies from about 500 MHz to 3 GHz. On some links, line-of-sight paths were unobstructed. Turin et al., concluded that, in their experiment, the multipath spread depended almost entirely on the local environment of the receiver. The results obtained at the three different frequencies were essentially the same. The total delay was always less than 7 µs and usually 5 µs for high rise portions of the city. Smaller towns and suburban areas showed spreads of 3 µs to 4 µs.

Local multipath statistics for a suburban area are described by Cox (1972a and 1972b) based on measurements along several business and residential streets in suburban New Jersey. He presents data in the form of average delay profiles, cumulative distributions of signal amplitude at fixed delays and frequency shift spectra at fixed delays. Typical delay spreads for the suburban area are 0.25 µs although in extreme cases significant components were observed with excess delays from 5 µs to 7 µs and the rms delay spread was approximately 2 µs.

Multipath profiles in urban areas of New York City have also been measured by Cox (1973) using similar analysis, measurement equipment, and presentation of the data. In some locations significant amplitudes were observed with excess delays of 9 µs to 10 µs. The rms delay spreads for these areas were 2 µs to 2.5 µs. Cox concludes from his results that it appears reasonable to model the urban radio channel as a Gaussian quasi-wide-sense stationary uncorrelated scatter channel (Bello & Nelin, 1963), at least within a bandwidth of 10 MHz and for intervals up to 30 meters along the street.

Nielson (1975) measured various mobile channel characteristics at 1340 MHz along several paths in areas around San Francisco. Nielson classifies different paths by degree of urbanization into five terrain categories: dense urban, moderate urban, limited urban, suburban, and rural. He finds however, that this classification does not reflect large differences in the impulse responses observed. The total time delay spread varied from 5 µs to 6 µs in the urban areas to less than the equipment resolution capabilities (50 ns) for direct line-of-sight paths. The spread over intermediate terrain categories fell between these extremes but was essentially undifferentiable.

More recently (July 1977) the equipment used by ITS and described by Linfield et al. (1976) was employed to measure the impulse response at 8.6 GHz on mobile links in Boulder, Colorado. The delayed power spectra (including quadrature phase components) are being recorded on magnetic tape for subsequent analysis on the laboratory's analyzer and computer. Although this analysis has not been completed, it is of interest here to show some of the responses obtained because of the high resolution of the equipment and the higher carrier frequency used.

Figure 7 is a series of oscilloscope photographs of the instantaneous envelope of the response measured along a suburban street in an area of one-story houses near the OT/ITS laboratory. The line-of-sight path to the transmitter is partially obscured by buildings and trees. The three pictures were taken with the receiving terminal stopped at three points about 3 meters apart. The total delay varies from about 50 ns to 100 ns over this distance.

Figure 8 illustrates oscilloscope photographs taken one block south of the previous site. Both photographs were taken at the same location while the receiver terminal was stationary. Trees with foliage were blocking the line-of-sight path to the transmitter. The upper photograph contains only a few responses whereas the lower photograph shows several hundred responses averaged by the storage oscilloscope over a one-minute period. Ten sweeps were obtained each second. The maximum spread observed is about 120 ns. Fast changes in amplitude were attributed to the movement of the trees and their foliage which changes the attenuation on the paths at this frequency.

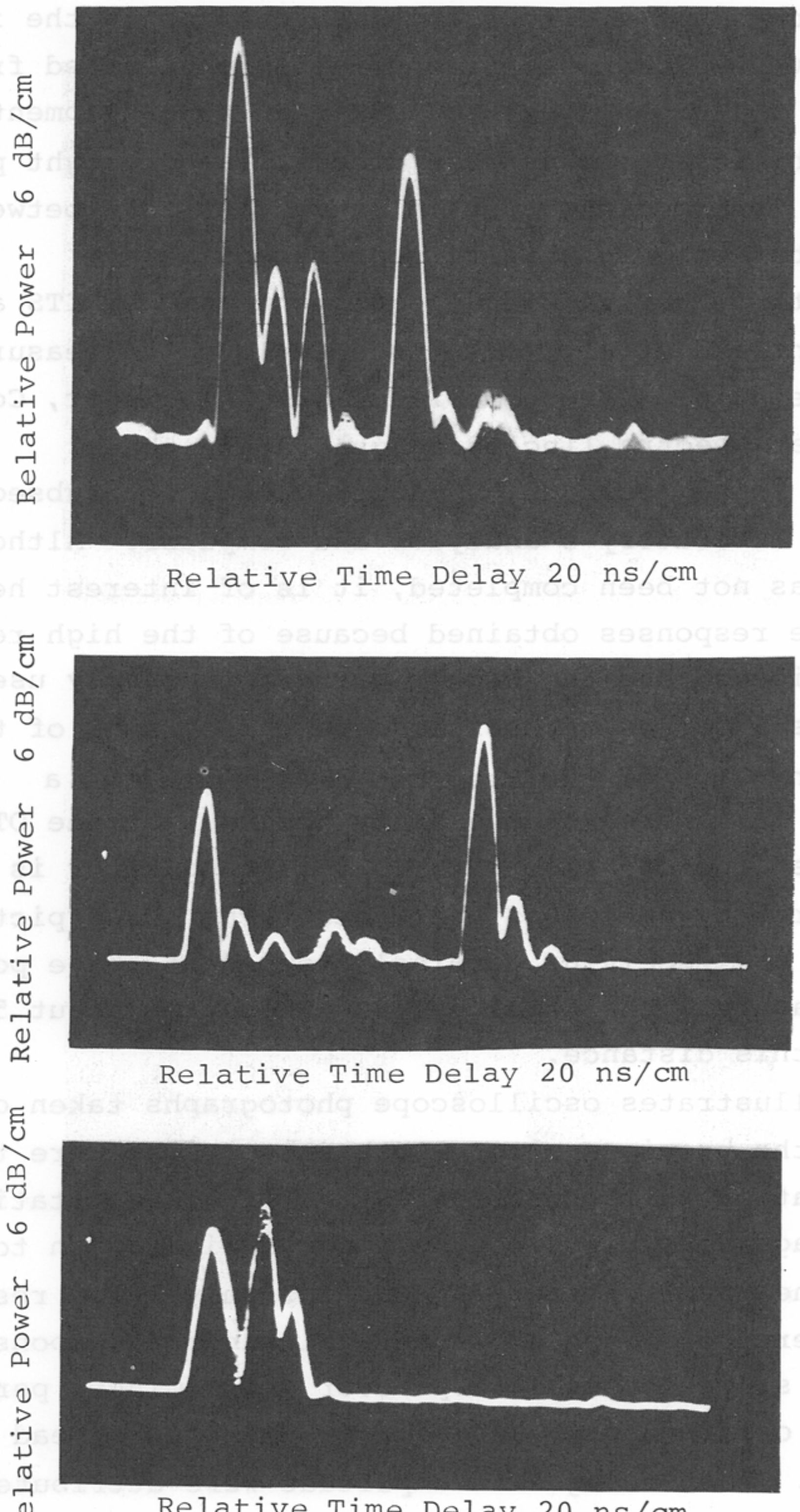



Figure 7. Impulse responses obtained 3 meters apart near one story housing area.

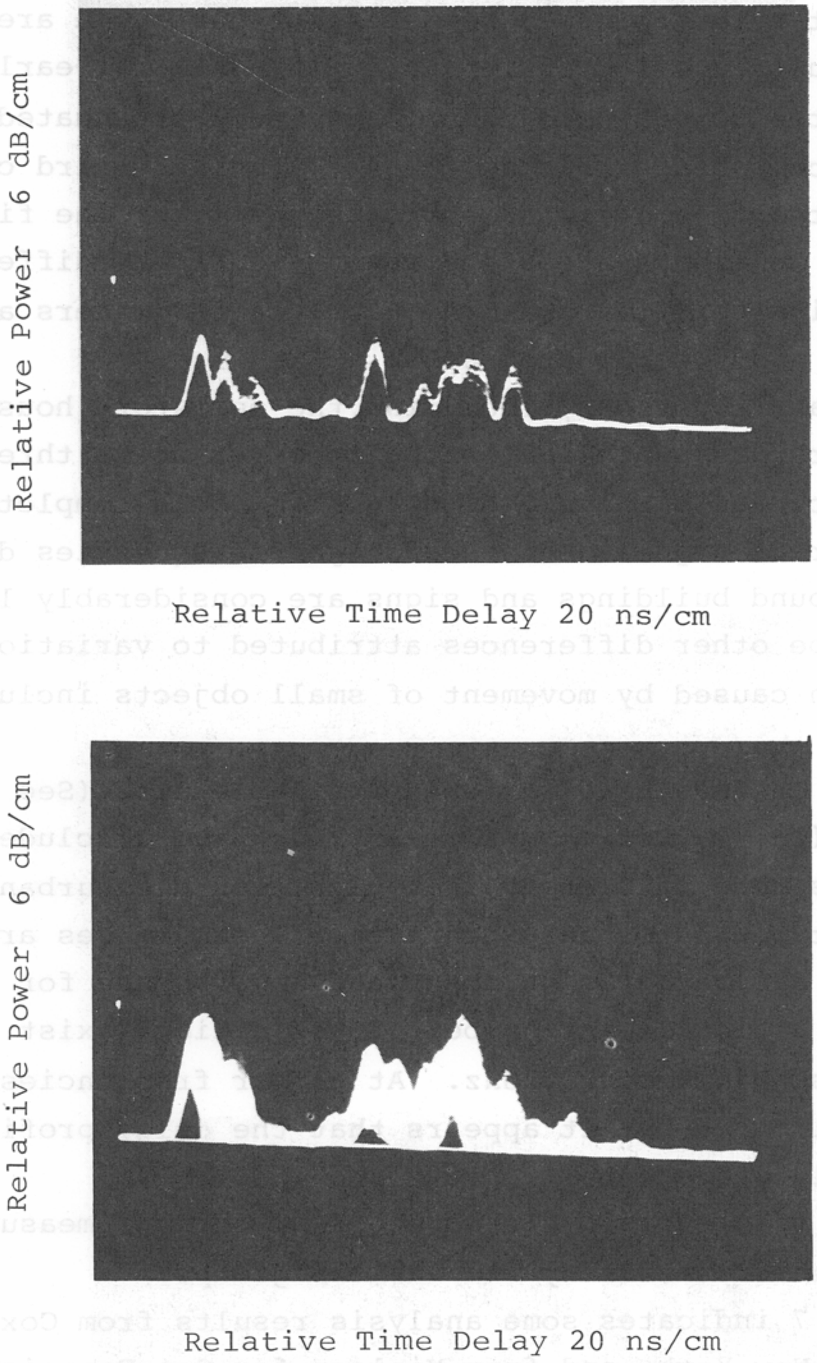



Figure 8. Single and multiple impulse responses at fixed location.

The photographs shown in Figure 9 were, like those in Figure 7, taken at three points 3 meters apart but in an area of fairly isolated multi-storied apartment buildings. The earliest arriving signal in the upper photograph is severely attenuated over a reflected component arriving 200 ns later. A third component of significant amplitude also occurs 320 ns after the first component. The multipath structure appears entirely different when the reception point is changed by only a few meters as shown by the middle and lower photographs.

For many locations, including the one-story housing area, signals were attenuated below the receiver noise threshold. Even small structures such as a highway sign could completely block out the direct signal. At these higher frequencies diffraction effects around buildings and signs are considerably less. There appear to be other differences attributed to variations in attenuation caused by movement of small objects including foliage on trees.

Other authors have reviewed available data (See Jakes (1975) and Clark (1968), for example) and they have concluded that an rms delay spread of 0.25 μs is typical for a suburban area and 2.5 μs is typical for an urban area. These values are probably reasonable estimates as an upper and lower bound for almost any area where a significant number of reflections exist and for frequencies below about 3 GHz. At higher frequencies data are extremely limited but it appears that the delay profile may be considerably different.

Table 6 summarizes the total delay spreads measured in different environments by the various groups.

Table 7 indicates some analysis results from Cox for New Jersey and New York, and from Nielson for San Francisco. The rms spreads shown for San Francisco are averages from several hundred records. Specific values varied approximately ± 1 μs from these averages. No coherent bandwidths are given by Nielson. However, Dr. R.A. Whiteman (private communication) of the Electromagnetic Compatibility Analysis Center, Annapolis, Maryland, has computed

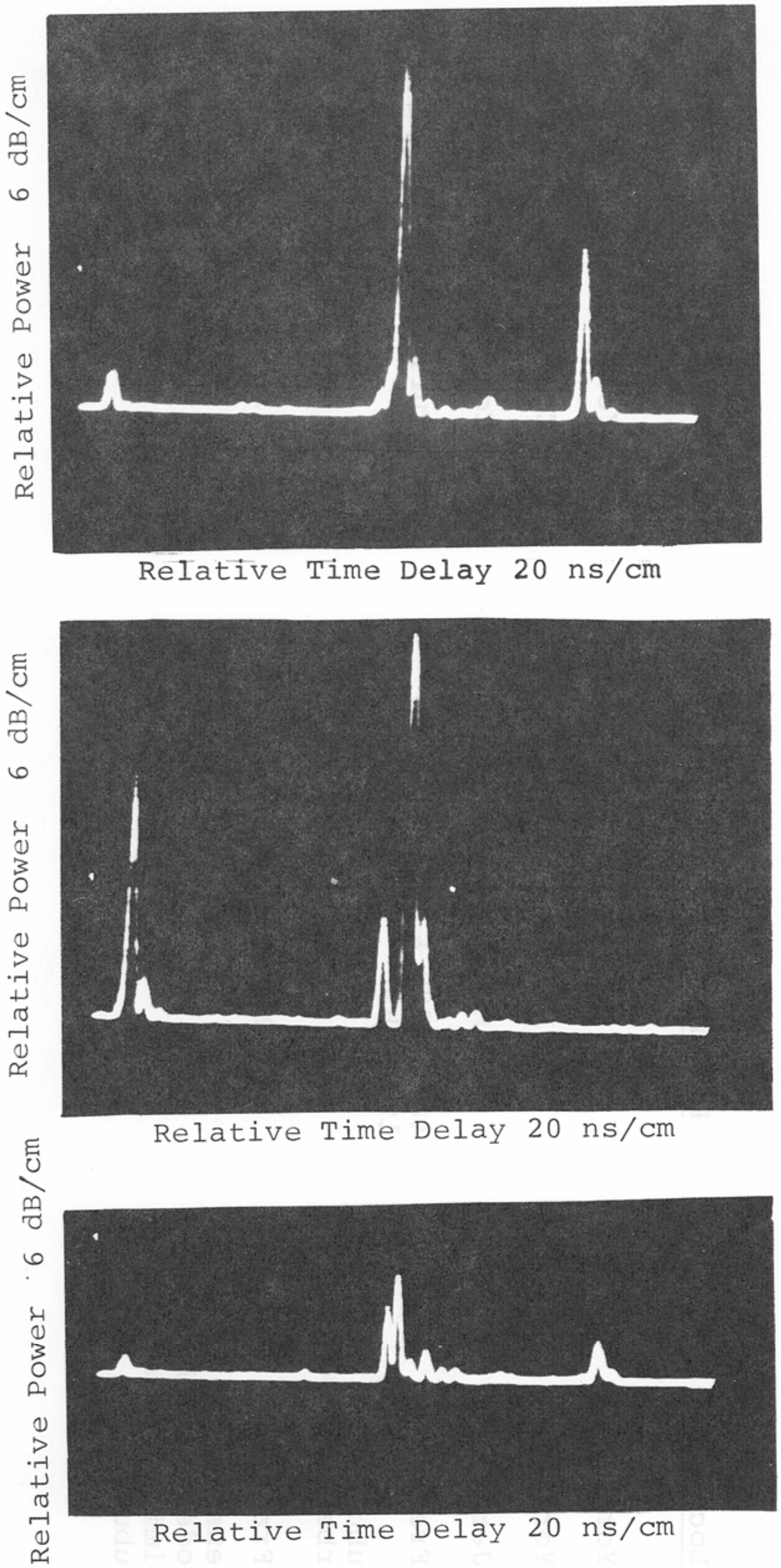



Figure 9. Impulse responses obtained 3 meters apart near high-rise apartment complex.

Table 6

Maximum Delay Spread Observed on Mobile Links

| Location | Frequency | Maximum Spread | Source |
|---|---|---|---|
| New York | 450 MHz | 5 μs | Young and Lacy (1950) |
| New York City | 910 MHz | 10 μs | Cox (1973) |
| New Jersey | 910 MHz | 6 μs | Cox (1972a & b) |
| San Francisco | 488, 1280 & 1920 MHz | | Turin et al (1972) |
| • Suburban | | 7 μs | |
| • Urban | | 4 μs | |
| San Francisco | 1370 MHz | | Nielson (1975) |
| • Dense Urban | | 5.5 μs | |
| • Moderate Urban | | 5 μs | |
| • Limited Urban | | 4 μs | |
| • Suburban | | 3 μs | |

Table 7

Statistical Measures of Delay Spread

| Location | Average Delay $\tau_o$ ($\mu s$) | Delay Spread $S_d$ ($\mu s$) | Profile Width -3dB ($\mu s$) | Profile Width -10dB ($\mu s$) | Coherence B.W. $\rho=0.9$ (kHz) | Coherence B.W. $\rho=0.5$ (kHz) |
|---|---|---|---|---|---|---|
| New Jersey | | | | | | |
| Annapolis Dr. | 0.15 | 0.24 | 0.22 | 0.38 | 300 | 3000 |
| Maple Place | 0.09 | 0.18 | 0.13 | 0.40 | 500 | 2700 |
| Main Street | 0.03 | 0.10 | 0.11 | 0.26 | 1000 | 9000 |
| American Legion Dr. | 1.90 | 2.05 | 1.20 | 4.50 | 40 | 90 |
| New York City | | | | | | |
| Price Street | 1.9 | 2.53 | 1.5 | 9.6 | - | - |
| Water Street #1 | 1.6 | 1.95 | 0.14 | 3.3 | - | - |
| Water Street #2 | 2.4 | 2.19 | 0.8 | 7.4 | - | - |
| San Francisco | | | | | | |
| Dense Urban | - | 2.5 | - | - | - | - |
| Moderate Urban | - | 2.5 | - | - | - | - |
| Limited Urban | - | 2.1 | - | - | - | - |
| Suburban | - | 1.6 | - | - | - | - |

the rms delay spread for one profile given by Nielson which represented an average of 100 profiles in an urban area. His results for an rms delay spread of $S_d$ = 2.25 μs yielded a coherent bandwidth of 34.2 kHz for a correlation coefficient of 0.9.

## 5.2 Frequency Dispersion on Mobile Links.

As a mobile terminal moves with a constant velocity a continuous wave signal transmitted at a carrier frequency will be received with randomly varying amplitude and phase. The maximum effective bandwidth of this received signal is bounded by a maximum frequency shift of $\pm V/\lambda$ where V is the terminal velocity and λ is the wavelength of the carrier frequency. At 1 GHz, for example, a vehicle traveling at 56 km/s (35 miles per hour), the bandwidth occupied by the cw signal is ± 50 Hz. This frequency spread or Doppler shift can be normalized in units of cycles per meter of travel by dividing by the terminal velocity. Frequency spreads have been measured and evaluated by Cox (1972a & b, 1973) for various points on the delay curve. The doppler spectra at different delays are quite different although none exceeded $\pm 1/\lambda$ cycles/meter. At 910 MHz where the measurements were made $1/\lambda = 3$ cycles/meter. By observing the shift spectra at different delays, Cox was able to deduce the direction of arrival of components producing dominant features on the power impulse response.

Aircraft and other moving reflectors in the path can cause increases in observed shifts, and significant variations in observed multipath profiles even when the transmit and receive terminals are stationary.

In some instances, Nielson (1975) observed significant variations when a dominant path became obstructed. Such variations could present serious communication problems for certain wideband systems; for example, modems which resolve individual paths by synchronizing on the strongest path. Loss of synchronization would then occur if this path disappears or is switched off momentarily by an obstruction.

## 6. RELATING LINK RESPONSE TO COHERENT BANDWIDTH

Coherence bandwidth is a function of the time dispersion. It defines the separation between two frequencies, which under dynamic conditions will fade essentially in unison. Signals whose bandwidths exceed the coherence bandwidth will be distorted because the phase and amplitude of different frequency components fade independently.

The coherence bandwidth, $B_c$, of a radio channel is considerably different from the bandwidth of a conventional filter or the ideal filter discussed in Section 2. Signaling power is severely attenuated at frequencies outside the ideal filter bandwidth, B, or the practical filter bandwidth, $B_T$, given in Section 2. A radio channel, however, can transmit power at frequencies which far exceed the coherent bandwidth. Signals whose bandwidth begins to exceed B or $B_T$ are quickly degraded while signals whose bandwidths begin to exceed B are only gradually degraded. Conventional filter bandwidths are usually defined by the -3dB points, i.e., the frequency separation between points on the response curve at one-half the peak power. Coherence bandwidth on the other hand is defined as the frequency separation where the correlation between the two frequencies falls to some specified value. Different correlation values have been specified in the literature ranging from 0.9 to 0.37 depending on the author's view, on the analytical approach, and on the particular system under consideration.

The single correlation coefficient used to define correlation bandwidth is obtained from the frequency autocorrelation function. This function may be measured directly (Gallager, 1964) or may be obtained by Fourier transform of the impulse response.

The exponential distribution of time delays was found by Clarke (1968) and Gans (1972) to be a reasonable fit to impulse response data obtained by Young and Lacy (1950) for mobile links operating at a frequency of 450 MHz in New York City. The exponential distribution function is also a good approximation to later measurements at higher frequencies by Cox (1972a & b) and Turin, et al., (1972) for suburban as well as urban areas.

The frequency autocorrelation function for the exponential distribution is given by Gans (1972) as

$$\rho = \left[ \frac{1}{1 + (2\pi \Delta f S_d)^2} \right]^{1/2} \tag{6-1}$$

where $S_d$ is the rms delay spread from Equation (5-1) and $\Delta f$ is the frequency separation.

A curve of the autocorrelation function $\rho$ versus $\Delta f$ is shown in Figure 10 for the exponential delay profile. Using this curve it is possible to define a coherent bandwidth, $B_c$, for any selected value of $\rho$. For example, when $\rho = 0.9$, then

$$B_c = \frac{1}{4\pi S_d} \tag{6-2}$$

and when the rms delay spread $S_d$=l microsecond, the coherence bandwidth $B_c$ = 80 kHz. Other values for $B_c$ as a function of $S_d$ and parametric in $\rho$ are plotted in Figure 11 for the exponential distribution.

Different values of $B_c$ are obtained for the same p as the assumed shape of the delay profile changes. Gans (1972) compared the autocorrelation function for the exponential, Maxwellian and two valued profiles. For values of $\rho$ greater than 0.75 his results indicate that the coherence bandwidth is only slightly dependent upon the shape of the profile. He, therefore, approximates the coherent bandwidth as $B_c$ = 1/8 $S_d$ since this corresponds to specific combiner degradation in diversity systems using a pilot tone for determining weighting factors.

Jakes (1975) indicates the relationship between rms delay spread $S_d$ and the coherence bandwidth for the Gaussian distribution is given by

$$B_c = \frac{\sqrt{2}}{\pi S_d} \tag{6-3}$$

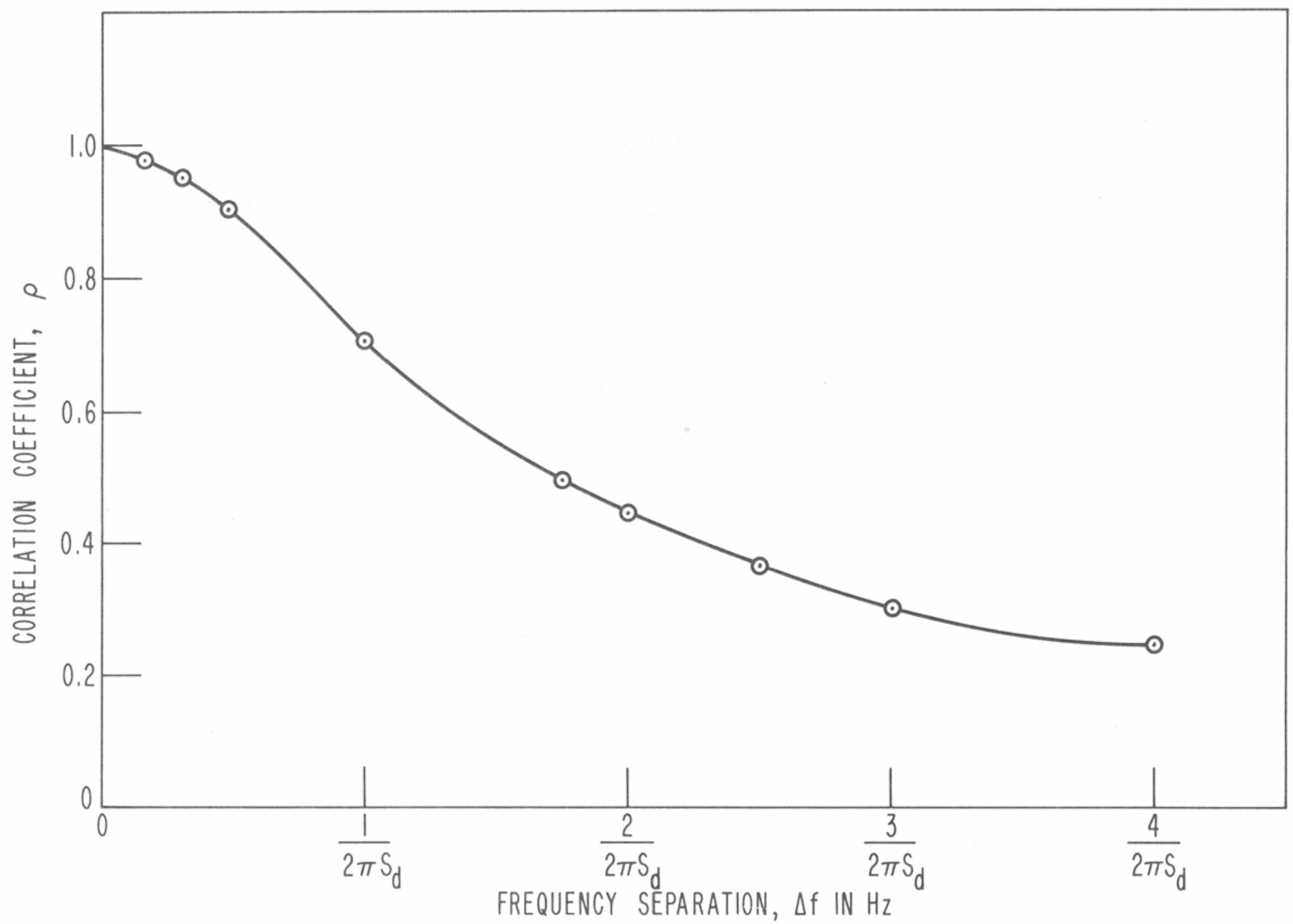



Figure 10. Frequency correlation function for exponential delay profile. $S_d$ is the rms delay spread.

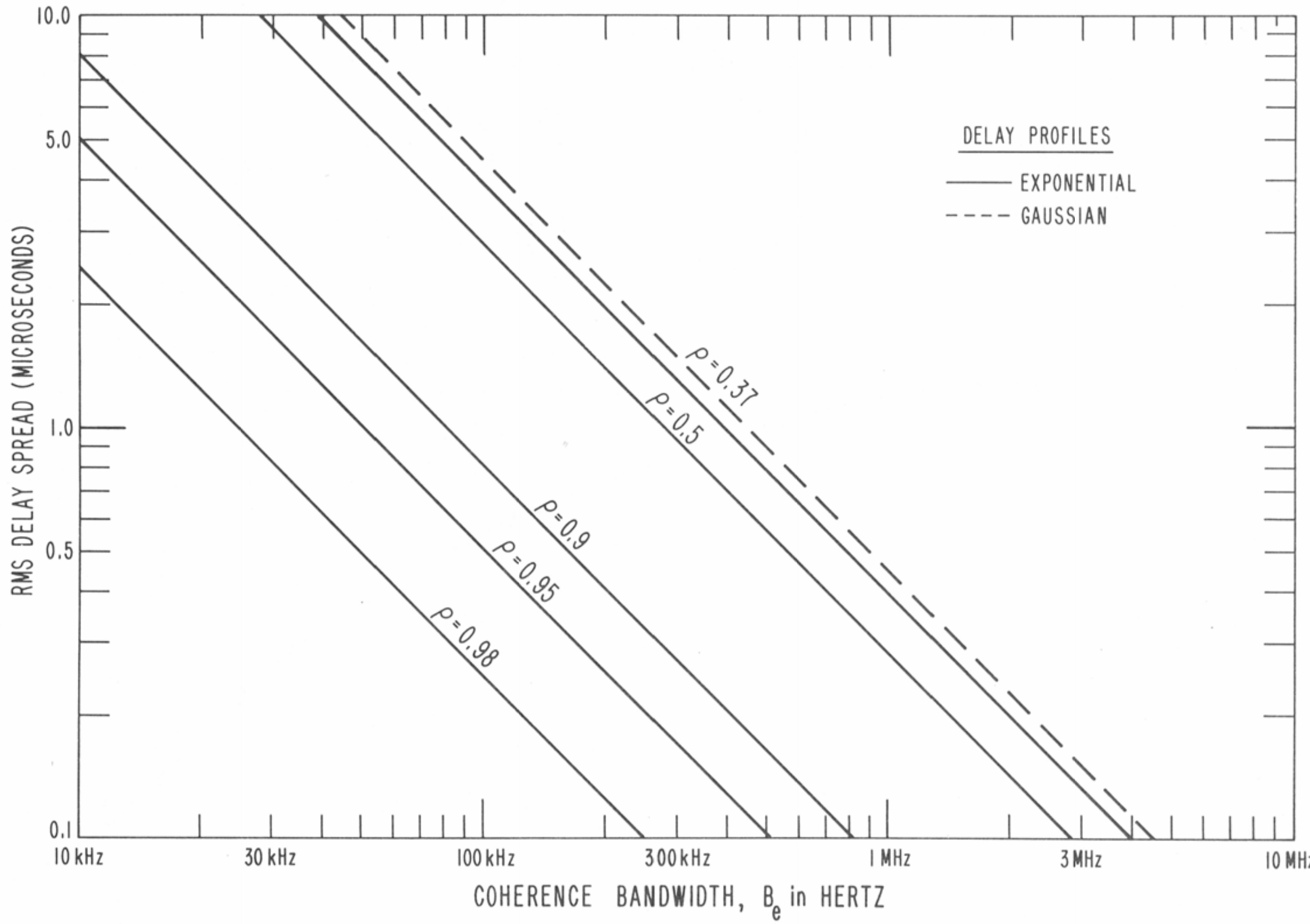



Figure 11. Coherence bandwidth curves for exponential delay profile parametric in correlation coefficient, ρ.

when the correlation coefficient falls to 1/e, i.e., $\rho = 0.37$. This is shown as a dashed line on Figure 11 and it is apparent that the coherent bandwidth for the exponential and Gaussian distributions are approximately the same for $\rho = 1/e$.

Bailey and Lindenlaub (1968) have theoretically compared the performance of a binary DPSK system using both Gaussian and rectangular delay profiles and using different symbol shapes. Their results show that there is a larger difference between achievable error rates when different signals are used in the same channel than when different channels are used for the same signal. This is also shown by Monsen (1973) discussing adaptive equalization techniques on a troposcatter channel. Monsen's computations indicated that the average probability of error was completely insensitive to the choice of shape of the delay power impulse response for a fixed ratio of $S_d$ to symbol width.

The results presented in Section 7 assume an exponential distribution for the channel impulse response with the coherence bandwidth defined at the $\rho = 1/e$ points as given in Figure 11.

## 7. RELATING COHERENT BANDWIDTH TO SIGNALING RATE

Bello and Nelin (1963) calculated error probabilities for a time dispersive channel and Gaussian noise for FSK and PSK systems which utilize diversity combining. They assume that the time-flat frequency-selective channel has a Gaussian impulse response and that the signaling element is rectangular. Bailey and Lindenlaub (1968) have extended these results for the PSK system to include a rectangular impulse response for the channel and a raised cosine signaling element.

One example of the performance obtained for the binary PSK system using differentially coherent detection is shown on Figure 12. The value for $B_c$ indicated on the selective fading curves is the correlation bandwidth for $\rho = 1/e$. The irreducible error rate caused by the frequency selective fading is indicated

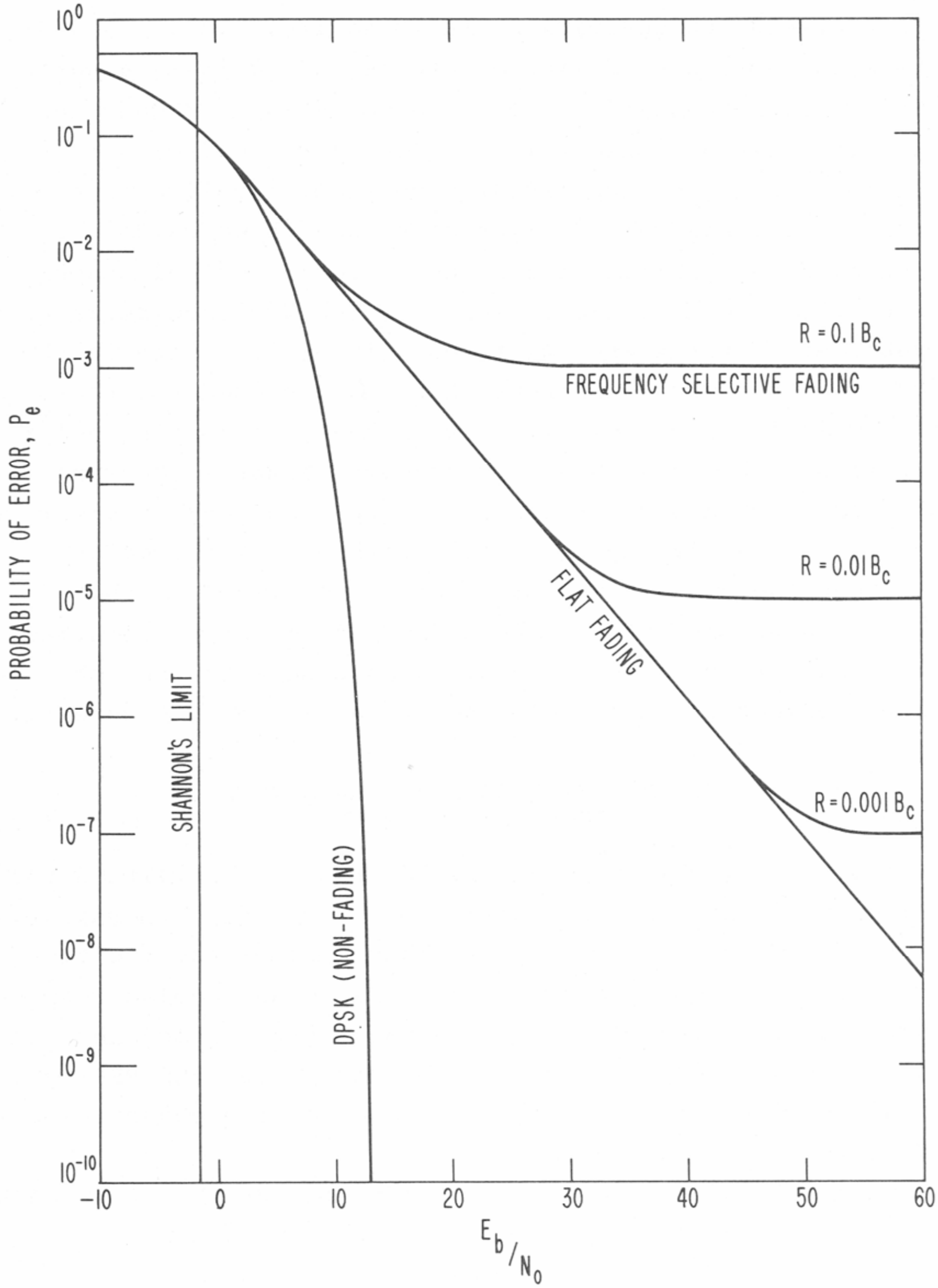



Figure 12. The effect of frequency selective fading on error probability for binary PSK systems. R is the signaling rate, $B_c$ the coherence bandwidth and the correlation coefficient $\rho = 0.37$.

for three different signaling rates in terms of $B_c$. When this irreducible error rate is reached, it cannot be changed by increasing signal power.

The irreducible error rates versus $1/\tau B_c$ and parametric in order of diversity, L, for differential PSK systems and non-coherent FSK systems are plotted in Figure 13, assuming a rectangular signaling element is used. The curves shown assume that the signaling rate is such that intersymbol interference from immediately adjacent symbols occurs.

At a fixed error rate it is possible using points from the curves in Figure 13 and the coherence bandwidth from the $\rho = 0.37$ curve in Figure 11 to relate the signaling rate to rms delay spread, $S_d$. Such curves are plotted in Figure 14 for both systems and parametric in L for an error rate $P_e = 10^{-5}$.

## 8. RELATING SIGNALING RATE TO SIGNAL POWER

In Section 7 and Figure 14, the signaling rate for two binary systems (PSK and FSK) operating at different levels of diversity (L=1, 2, and 4) was related to the rms delay spread, $S_d$, over a range from 0.1 μs to 10 μs. It was noted earlier that the data rate

$$R = \frac{1}{\tau}\log_2 m \, , \tag{8-1}$$

so that for cosine signaling with a binary system where m=2, the signaling rate is equal to the data rate, i.e., $R = 1/\tau$ bits/s. For cosine signaling with frequency roll-off of k=2, the signaling rate $1/\tau = B_T$ and the packing ratio is $R/B_T = 1$. Note that the ordinate is the data rate in bits/per second which for these binary systems corresponds to the signaling rate in symbols/s.

In Figure 15, the effect of the level of diversity, L, on the irreducible data rate is indicated for the case where the error rate $P_e = 10^{-5}$ and the rms delay spread $S_d = 1$ μs. As the L increases, the rate at lower signaling levels tends to approach the no-fading curves as expected. Ultimately, a transition point is reached when the rate cannot be increased by increasing the signal power.

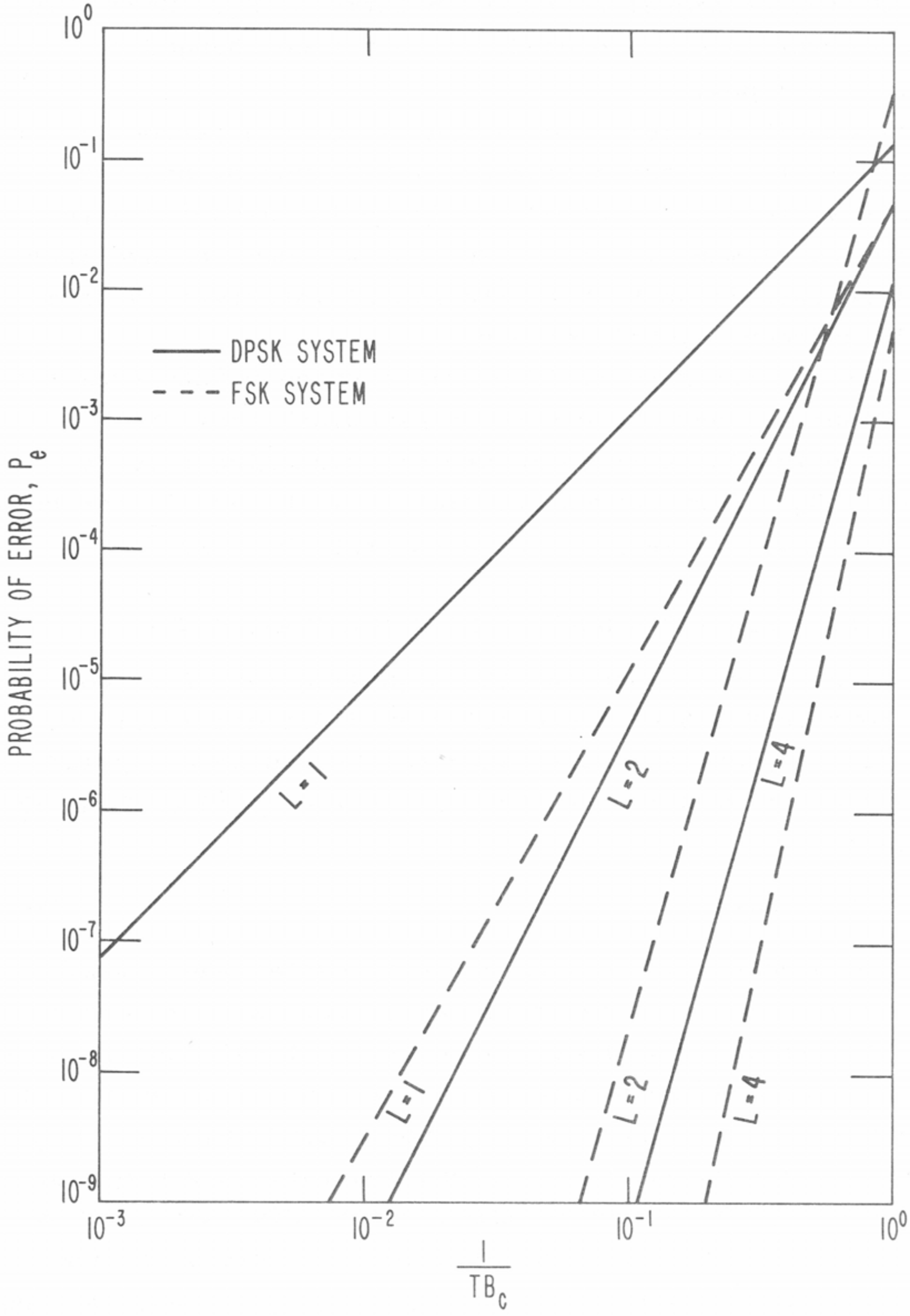



Figure 13. Comparison of irreducable error rates for binary DPSK and FSK systems parametric in level of density, L. T is the time to transmit one bit and $B_c$ the coherence bandwidth.

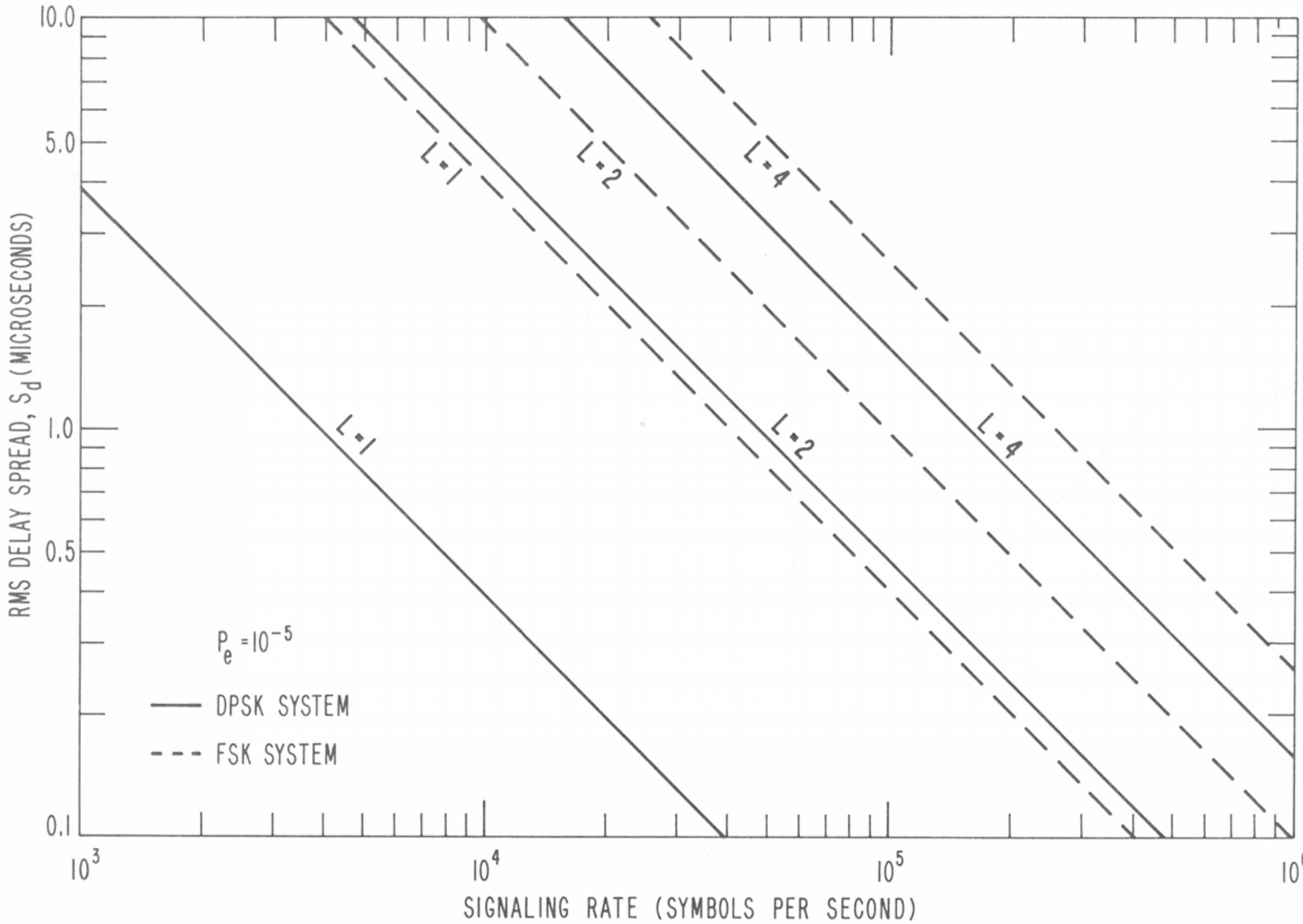



Figure 14. Relationship between rms delay spread and signaling rate for different levels of diversity, L, and for $\rho = 0.37$.

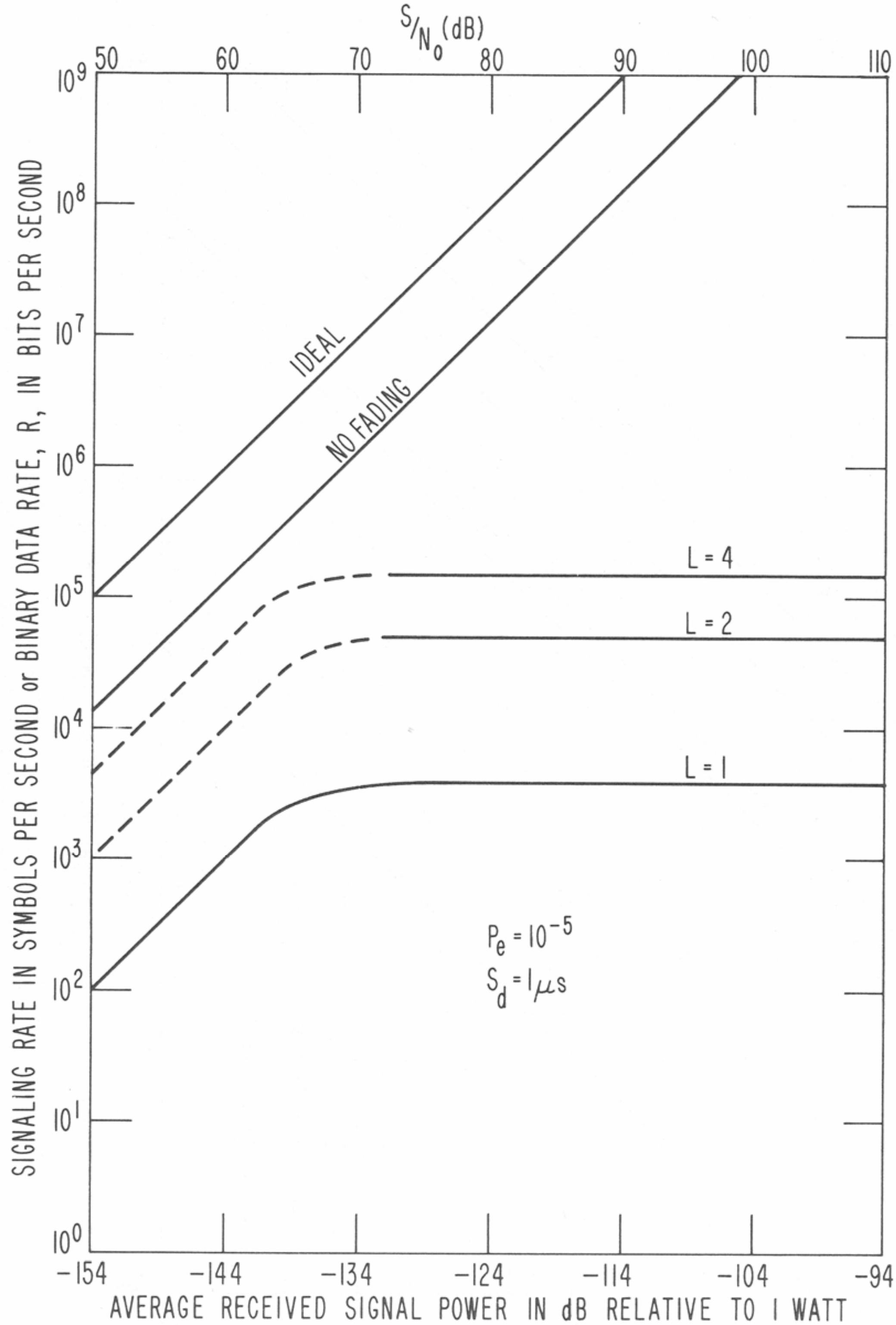



Figure 15. Diversity effects on data rate of the DPSK systems. L is the level of diversity and $S_d$ the rms delay spread.

In Figure 16, the level of diversity and the rms delay spread are held constant and the error rate allowed to vary.

For the curves plotted in Figure 17, the error rate is constant ($P_e = 10^{-5}$) and the parameters L and $S_d$ are varied. The curves are for the DPSK system. Figure 18 shows a similar set of curves for the non-coherent FSK system. The FSK system is less sensitive to the effects of frequency selective fading than DPSK, although DPSK is better than FSK by 3 dB for a flat-flat channel.

The maximum signaling rate for either system increases for both types of modulation as the order of diversity increases. The type of diversity used has a definite impact. In Figures 17 and 18 the rate increase is due to space diversity requiring the use of separate antenna configurations, separate receivers and post-detection combining. The use of such redundant channels is denoted as "explicit" diversity. The use of more than four explicit diversity levels is generally considered unpractical due to system complexity and economic consideration.

An alternative scheme utilizes the "implicit" diversity inherent in the channel itself. Implicit diversity may be interpreted physically as a time diversity produced by resolving multipath components in the dispersive channel. Multipath diversity has been used in the RAKE system to reduce fading effects in a flat-flat channel as described by Price and Green (1958). RAKE uses a spread spectrum carrier and a tapped delay line receiver that continuously measures the multipath structure and coherently combines the energy from various paths.

More recently Monsen (1971, 1973, 1974) described a multipath diversity system which employs a receiver having adaptive equalization with decision feedback. The system does not require a spread spectrum carrier for resolving the multipath components as RAKE does. Monsen shows that the dispersive effects of the channel can actually improve performance if a proper structure is employed to combine the available implicit diversity paths. A simulation of troposcatter channels indicates that high signaling rates could be realized with this scheme. The rates which could

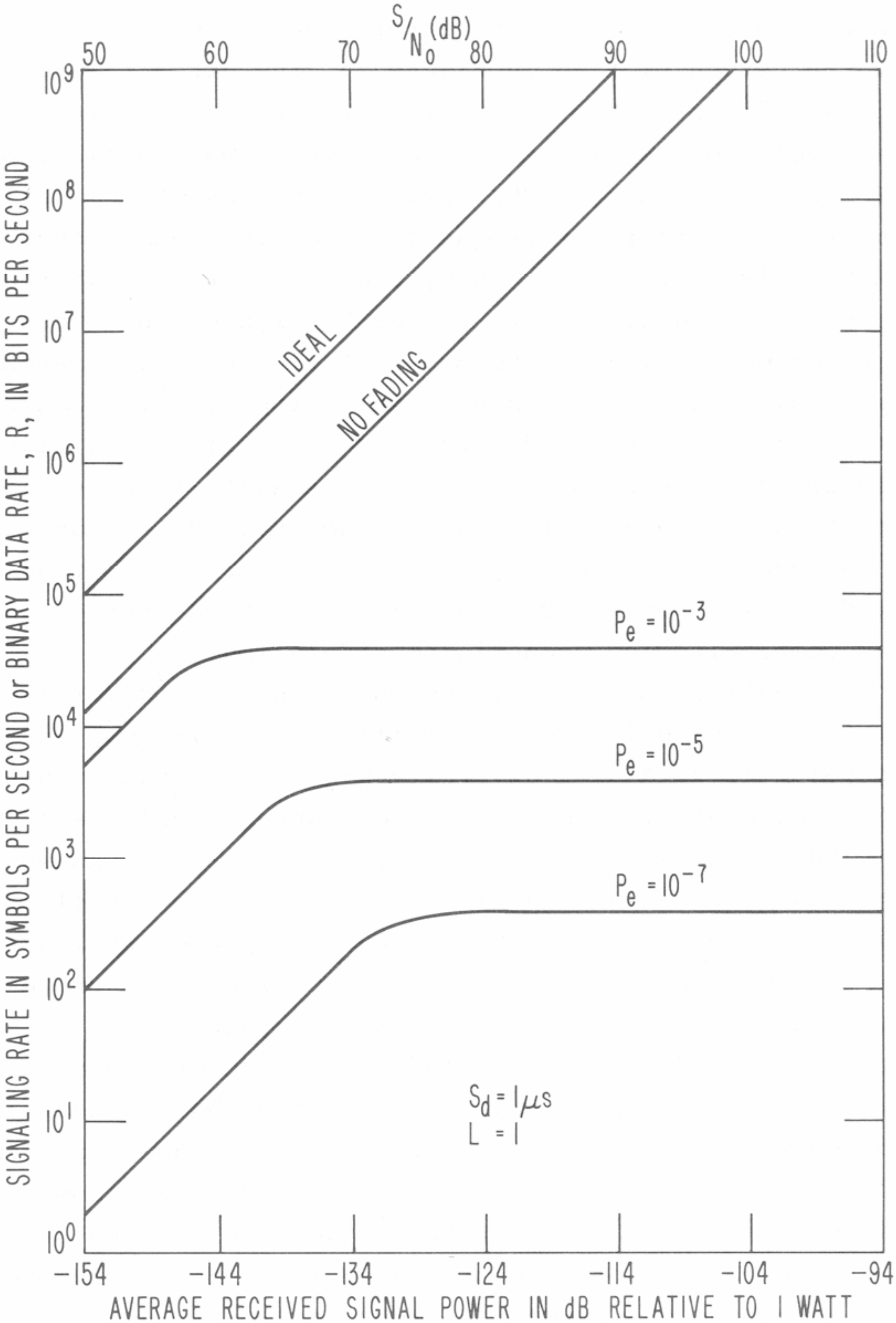



Figure 16. Error rate effects on data rate of the DPSK systems for non-diversity reception. $S_d$ is the rms delay spread.

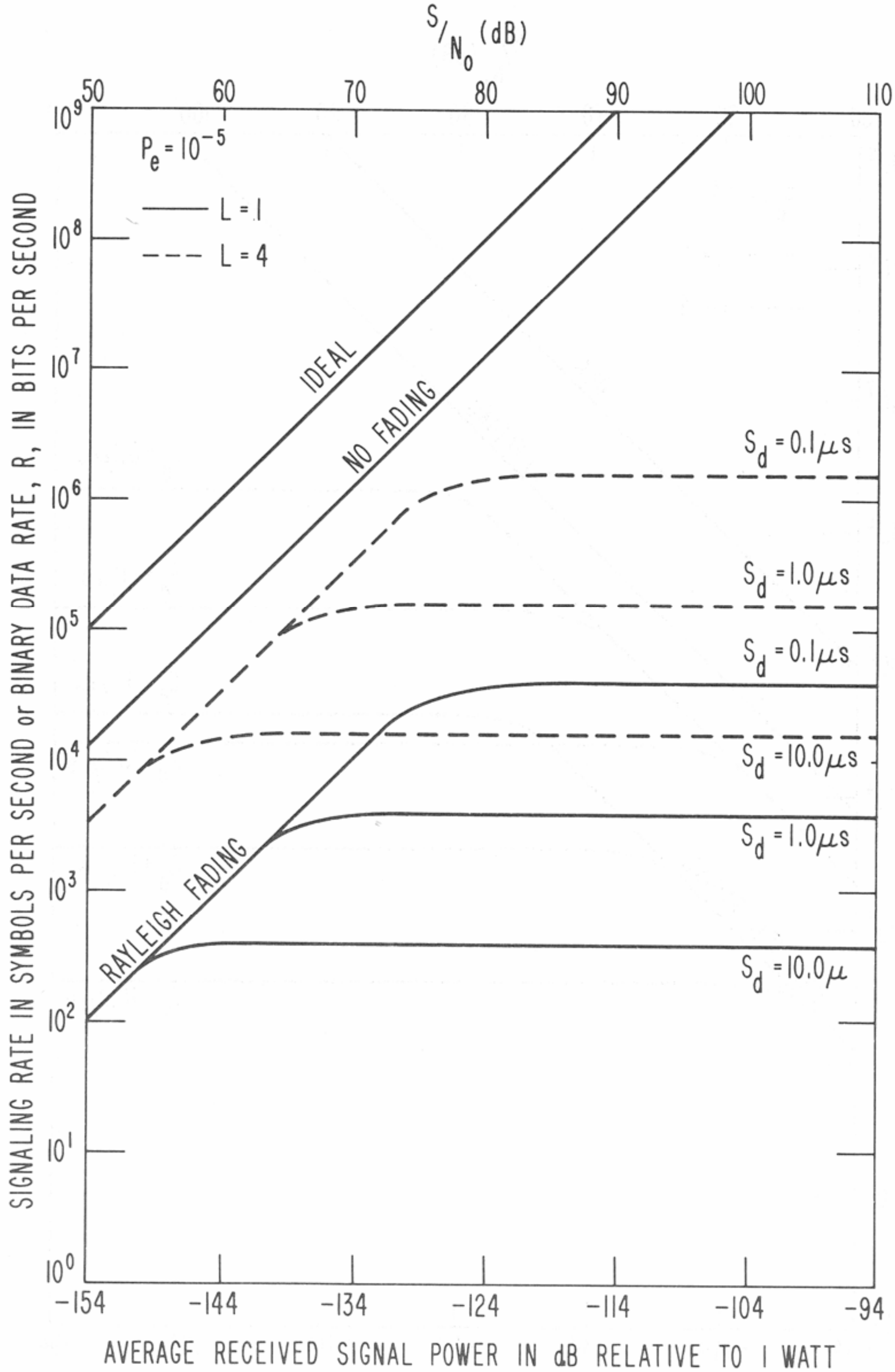



Figure 17. Root mean square delay spread, $S_d$, effects on data rate of the DPSK systems for different levels of diversity, L and fixed error rate.

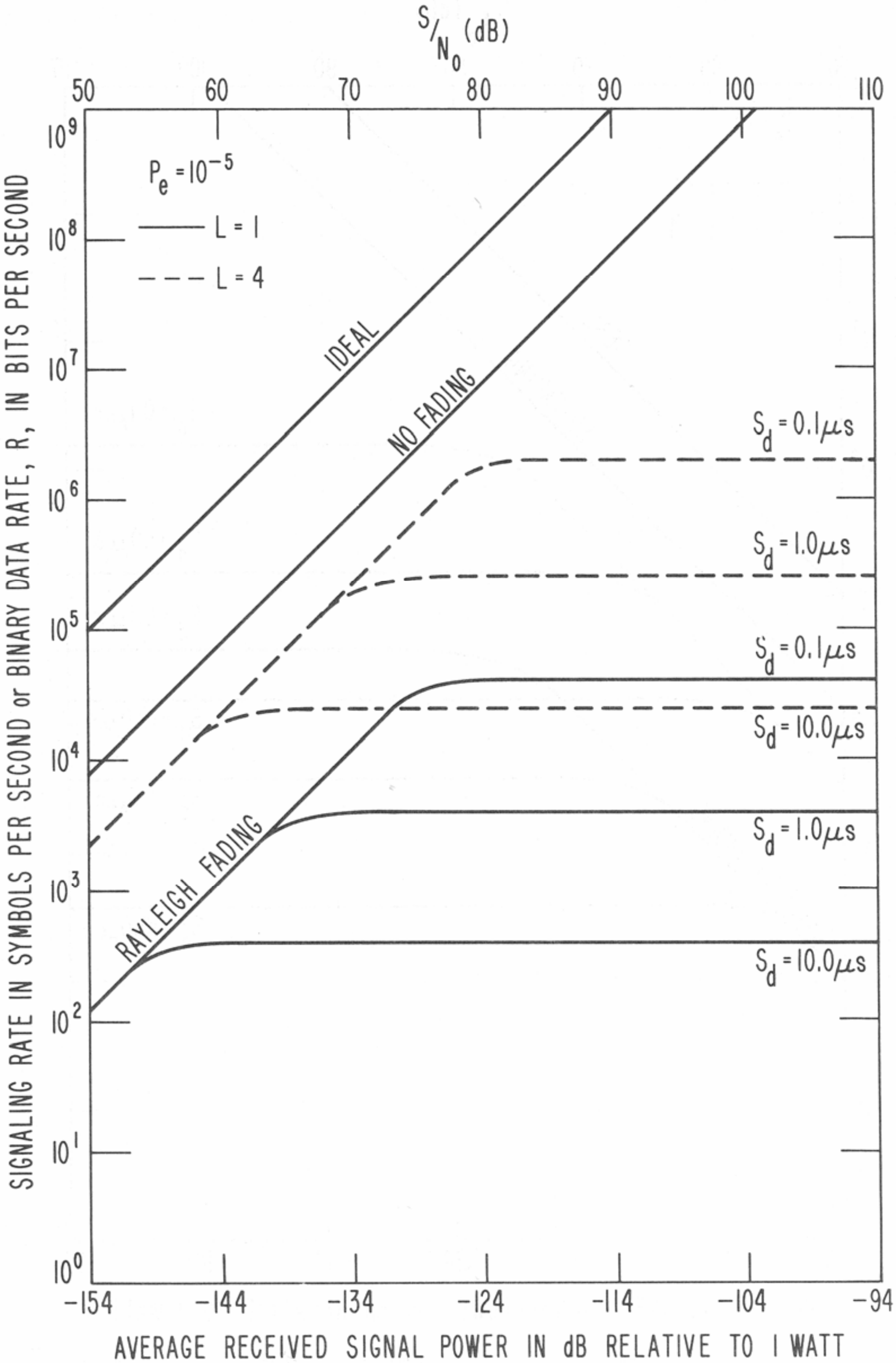



Figure 18. Root mean square delay spread effects on data rate of FSK systems for different levels of diversity, L, and a fixed error rate.

be realized are three times a rate equal to the inverse of the rms delay spread. Using both explicit and implicit diversity, the system performance, in terms of error rate and signal power required, approximates the performance attained in the case of no fading. The adaptive equalization technique is apparently only applicable to channels with slow time variations relative to the delay spread (e.g., a troposcatter channel). Whether this or similar techniques could be used in the mobile channel, where the frequency dispersion is much greater, is a matter of conjecture.

The signaling rates achievable for some rms delay spreads considered typical for mobile systems operating in urban and suburban environments are illustrated in Figure 19. As noted previously, the delay spreads of 0.25 μs and 2.5 μs are probably reasonable estimates for upper and lower bounds in almost any area where a significant number of reflections exist.

## 9. RELATING SIGNALING RATE TO DATA RATE

The previous section showed how the signaling rate (or binary system data rate) for a given modulation scheme depends on a) the delay spread, b) the acceptable error rate, and c) the level of diversity. A question still to be answered is how much can the data rate be increased for a fixed signaling rate by sending more bits per symbol assuming the bandwidth is limited and the transmitter power is not limited.

Each symbol in a stream of symbols can be made to convey more than one bit of information by letting one symbol characteristic assume several distinguishable states or by varying more than one characteristic.

An example of the effect on one systems data rate is indicated in Figure 20 for an m-ary PSK system assuming $P_e = 10^{-5}$, L=1 and $S_d$ = 1 μs. The solid line corresponds to a PSK system with R/B=2 and the dashed line to R/B=8. It is apparent that increasing the maximum data rate by a factor o£ four over coherent bandwidth limited channels for this system requires a substantial increase in received power to maintain the same error rate.

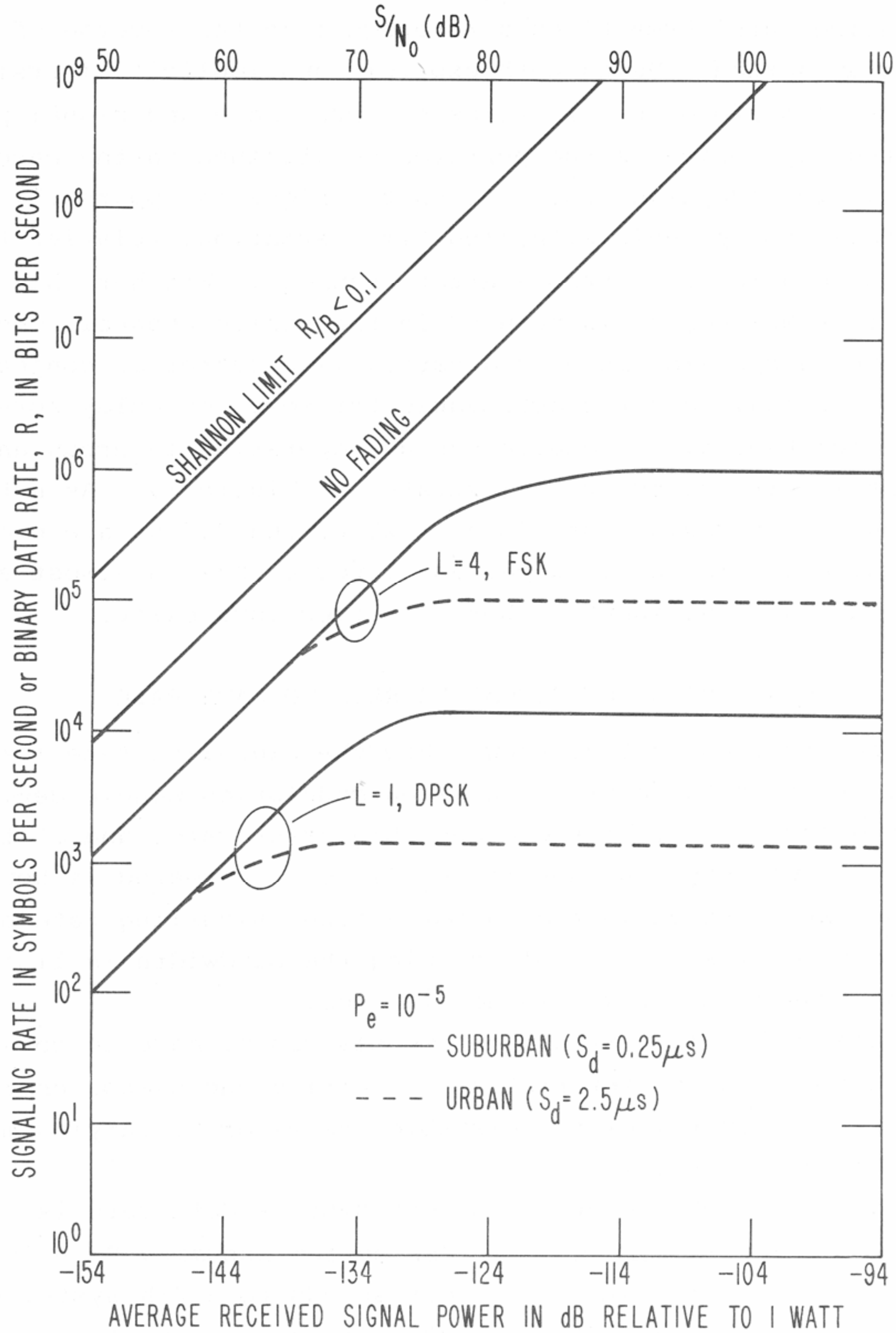



Figure 19. Rates achievable in typical mobile environment. $S_d$ is the rms delay spread and L the level of diversity.

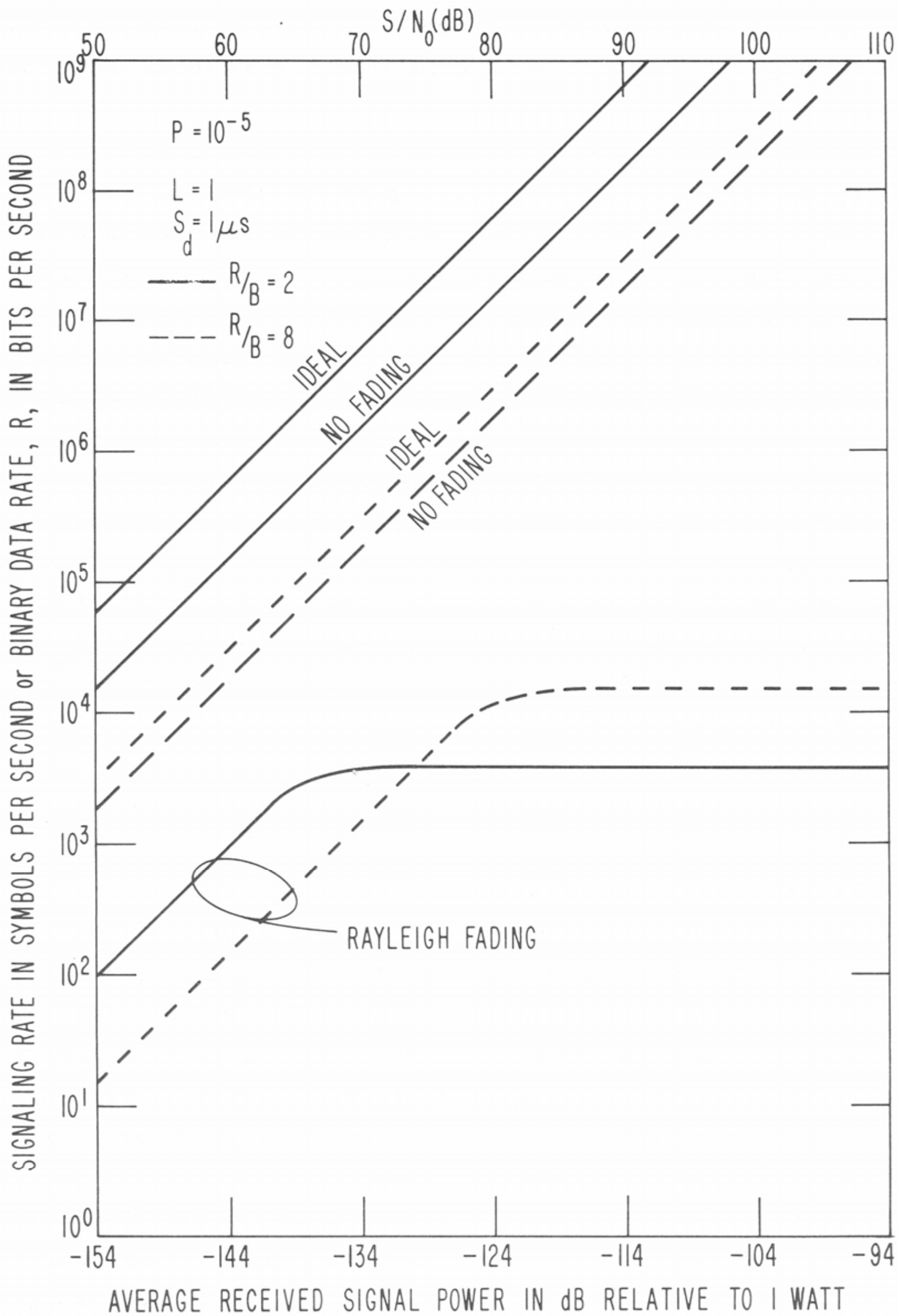



Figure 20. Effect of packing ratio on data rate of m-ary PSK systems. $S_d$ is the rms delay spread and L the level of diversity.

It was noted previously in Section 2 that, for this reason, there is not much point in letting R/B be greater than approximately 10.

Maximizing the packing ratio within these limits is obviously one way to increase data rate as long as the signaling rate is such that no selective fading occurs. Such a signaling rate means that the occupied bandwidth does not exceed $KB_c$. If the allocated bandwidth $B_a$ is greater than $KB_c$, then one way the data rate can be increased by occupying more bandwidth while not increasing the signaling rate is to utilize additional transmitting frequencies. The number of adjacent channels that can be used depends on the bandwidth occupied by the signal in each and on the filter design required to separate the channels.

If there are n frequencies transmitted one at a time with m types of symbols per frequency, then the total information conveyed is log nm bits/symbol. If each channel is $KB_c$ wide then the total bandwidth $B_a$ required is $nKB_c$ (assuming ideal filtering) and therefore

$$R/B_a = \frac{\log nm}{n} \tag{9-1}$$

which reaches a maximum when n=3.

Values for $n=B_a\tau$ vs. $R\tau = \log mn$ have been plotted in Figure 21. Here it is assumed that the n frequencies are separated by $1/\tau$ and ideal filters are used. The actual data rate achieved in a practical system using non-idealized filters would be less depending on the response of the filters employed. Note that information can be transferred when m=1 as long as n is greater than 1.

As an example, assume that a 50 kHz bandwidth has been allocated for a mobile link in a suburban environment where $S_d$ = 0.25 μs. The maximum undistorted signaling rate from Figure 19 is about 10 k symbols/s for a DPSK system with no diversity (L=1). Therefore

$$n = \frac{50k}{10k} = 5 \tag{9-2}$$

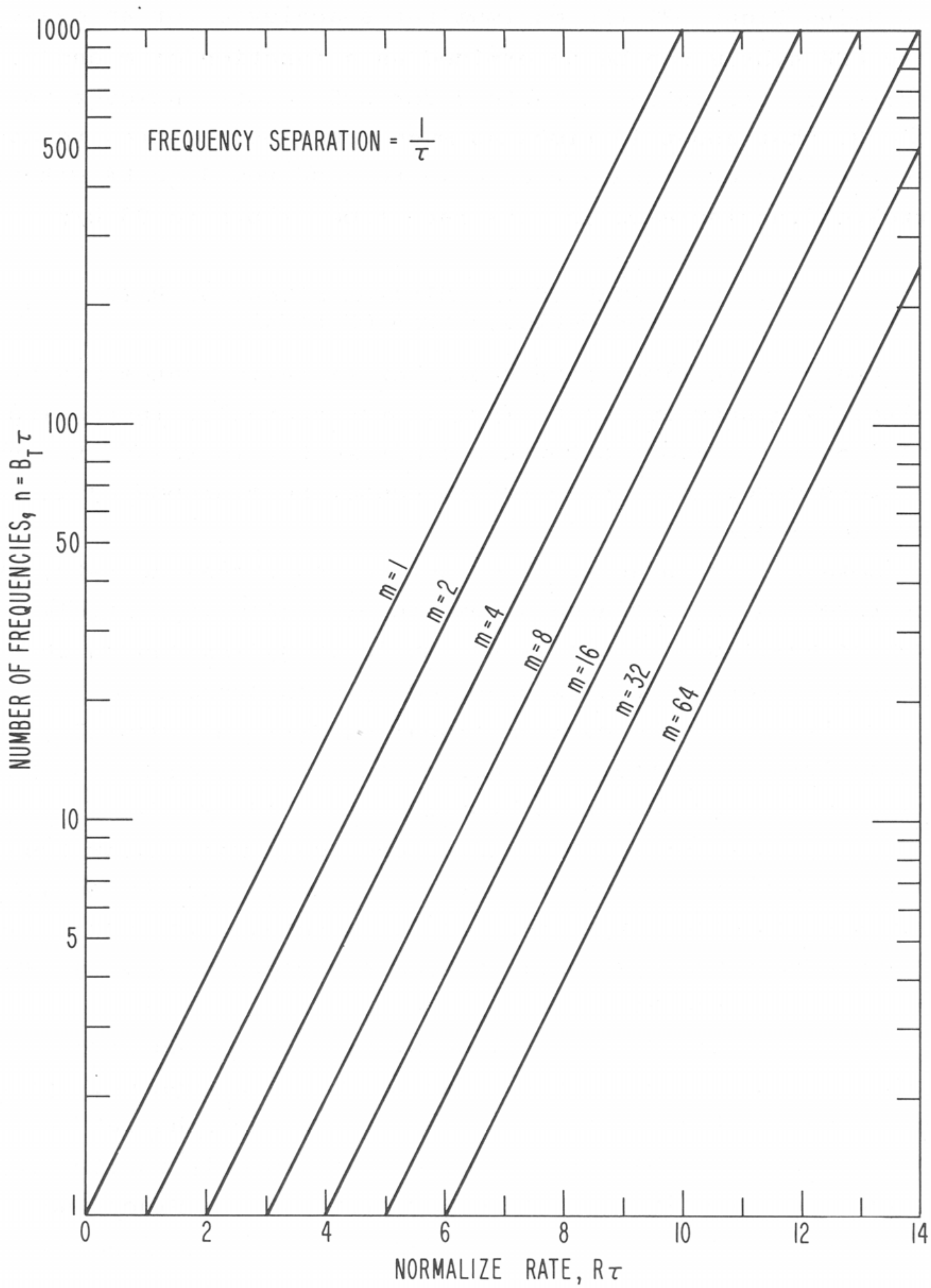



Figure 21. Normalized rates for m-ary PSK, n-ary FSK systems. $B_T$ is the total bandwidth and $\tau$ the time to send one signaling element.

Using Figure 21 the maximum rates achieved for an m-ary PSK, n-ary FSK system can be determined as a function of m and n. Results are tabulated in Table 8 for n=5. Note, however in Table 8, that about 10 times as much power is required to maintain the same error rate when m increases from 4 to 64 with a corresponding increase in data rate from 43 b/s to 83 b/s.

## 10. ESTIMATES OF THE MAXIMUM SIGNALING RATE FOR VARIOUS TYPES OF LINKS

Previous sections have shown how signaling rates may be limited by dispersive mechanisms in the channel. Increasing the signaling rate beyond a certain limit merely increases the number of errors observed. These errors cannot be overcome by increasing signal power.

However, at an acceptable undistorted signaling rate, the data rate can be increased almost indefinitely if sufficient power is available. This is accomplished by increasing the number of information bits conveyed by each symbol.

Estimates of the maximum signaling rate in symbols/s, have been derived for certain systems operating over channels where the rms delay spread varies from 100 ns to 10 μs.

The actual spread observed depends on a particular type of link. In Figure 22, the estimated maximum signaling rates for various types of binary links are illustrated. The data used to develop Figure 22 were obtained from a variety of sources which are given in Table 9.

These results do not include systems employing wideband carriers, e.g., spread spectrum systems. Even when multipath conditions exist a wideband carrier with bandwidths 100 to 1000 times the coherent bandwidth may, with a properly implemented receiver, resolve individual propagation paths. Since these individual paths are extremely broadband, when the receive process isolates one path, the coherence bandwidth limitation no longer exists.

Table 8

Maximum Rates Achievable in 50 kHz Allocated Bandwidth with m-PSK, n-FSK System

Suburban ($S_d$ = 0.25, n = 5)

| m | $R\tau$ | $1/\tau$ (Symbols/s) | R (bits/s) | $R/B_a$ (bits/s/Hz) |
|---|---|---|---|---|
| 1 | 2.3 | 10 k | 23 k | .46 |
| 2 | 3.3 | 10 k | 33 k | .66 |
| 4 | 4.3 | 10 k | 43 k | .86 |
| 8 | 5.3 | 10 k | 53 k | 1.06 |
| 16 | 6.3 | 10 k | 63 k | 1.26 |
| 32 | 7.3 | 10 k | 73 k | 1.46 |
| 64 | 8.3 | 10 k | 83 k | 1.66 |

Urban ($S_d$ = 2.5, n = 50)

| m | $R\tau$ | $1/\tau$ (Symbols/s) | R (bits/s) | $R/B_a$ (bits/s/Hz) |
|---|---|---|---|---|
| 1 | 5.6 | 1 k | 5.6 k | 0.112 |
| 2 | 6.6 | 1 k | 6.6 k | 0.132 |
| 4 | 7.6 | 1 k | 7.6 k | 0.152 |
| 8 | 8.6 | 1 k | 8.6 k | 0.172 |
| 16 | 9.6 | 1 k | 9.6 k | 0.192 |
| 32 | 10.6 | 1 k | 10.6 k | 0.212 |
| 64 | 11.6 | 1 k | 11.6 k | 0.222 |

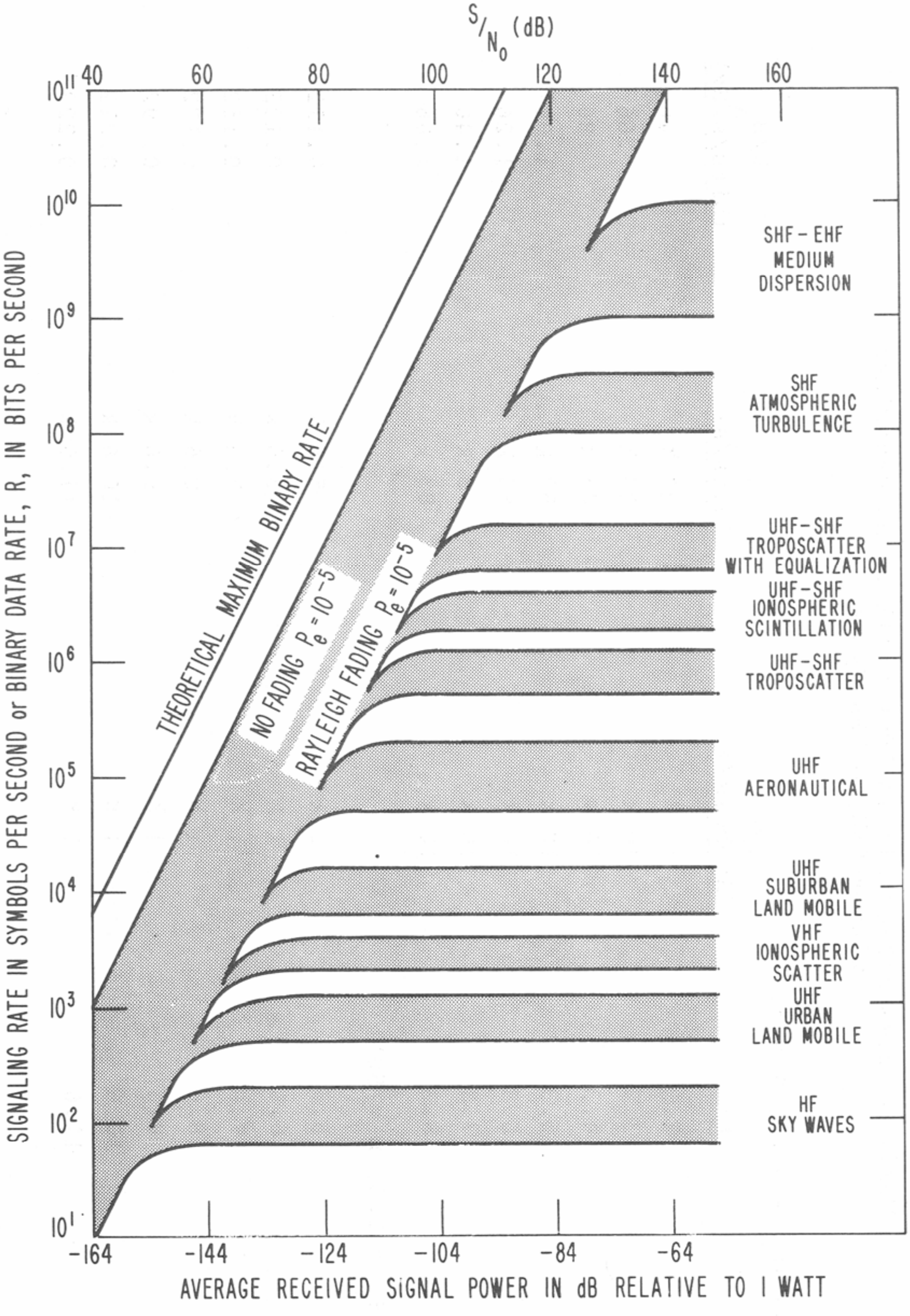



Figure 22. Rate limits on some binary links and channels.

Table 9

Data Sources for Figure 22

| Channel | Source Reference |
|---|---|
| EHF & SHF Medium Dispersion | Ma and Dougherty (1976)<br>Roche, et al. (1970) |
| SHF Atmospheric Turbulence | Bello et al. (1973a) |
| SHF Atmospheric Multipath | Dougherty and Hartman (1977) |
| UHF-SHF Troposcatter with Adaptive Equalization | Monsen (1971, 1973, & 1974) |
| UHF-SHF Ionospheric Scintillation | Nesenbergs and Ott (1974, Private Communication) |
| UHF-SHF Troposcatter | Schartz, et al. (1966)<br>Bello (1969a, 1969b) |
| UHF Aeronautical | Frasco and Goldfien (1973)<br>Sutton, et al. (1973)<br>Schnieder (1973) |
| UHF Land Mobile Urban and Suburgan | This Report (Fig. 19, L=1) |
| VHF Ionoscatter | Schwartz, et al. (1966) |
| HF Skywaves | Schwartz, et al. (1966) |

## 11. COMPARING WIDEBAND TACTICAL NETS WITH FM (30-76 MHz) SYSTEMS

It would be useful to compare the results presented here with results obtained from actual wideband systems operating at high data rates comparable with those which appear realizable. Unfortunately, such data are severely lacking for mobile links. There are, however, some data on the use of VHF-FM radios in Army Tactical Data Systems where a number of sets share a common frequency in the 30 MHz to 76 MHz band with a 50 kHz channel spacing. A summary is given by Tucker (1972).

The operational characteristics of typical FM tackical radio equipment are as follows*

| Equipment Descriptor | **Transmitter** Power (watts) | **Frequency** Rated (kHz) | Deviation Used (kHz) | Necessary Bandwidth (kHz) |
|---|---|---|---|---|
| AN/PRC-25 | 2 to 3 | ±8 | ±5 | 16 |
| AN/VRC-12 | 35 | +8 | +5 | 16 |

A center-fed whip antenna is normally used with no diversity. Tests were conducted by Salava (1970) using a FT-524/VRC-12 radio set having a 3 kHz bandpass characteristic for voice band and 17 kHz bandpass characteristic for the wideband mode. Data on error rate vs. signal-to-noise ratio were obtained at 300, 600, and 1200 bits/s over ranges from 2 miles to 22 miles*. The average bit error rate varied inversely as the ratio. This relationship would be expected for a Rayleigh fading channel or additive impulsive noise. At the maximum rate of 1200 bits/s an irreducible error plateau was not apparent at least within the minimum error rates presented ($P_e \approx 10^{-6}$). The multipath disturbances which were experienced were attributed by Salava to low flying aircraft in the vicinity of the test area and possibly passing vehicles.

Similar tests were performed by Ebisu and Leen (1971) at 120 b/s using FSK modulation over non-line-of-sight paths where

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*Private communication from Electromagnetic Compatibility Analysis Center, Annapolis, Maryland.

the intervening terrain varied from relatively flat to hilly. Analysis of the errors attributable to fading was difficult to quantify because other error-causing factors (lightning and ignition noise) were also present. At these rates, however, one would expect the fading to be flat, i.e., non-frequency selective.

Tests at higher data rates of 19 k bits/s were performed by Mikulski (1969) of Motorola Inc. using the same AN/VRC-12 equipment. An irreducible error rate at approximately $2x10^{-4}$ was attained but this was attributed primarily to the response of the radio set operating in the wideband (17 kHz) mode. This error rate was deemed acceptable for digitized voice transmissions. During periods of signal distortion due to multipath Mikulski experienced difficulties in maintaining bit synchronization. A movement of just a few feet caused the error rate to change from a low value to $5 \times 10^{1}$. The multipath spread is unknown. This effect may be attributed to obstructions momentarily appearing in the path which suppress the dominant path as described in Section 3.3. Multipath effects caused by aircraft were observed at ranges exceeding 16 miles (26 km). Multipath from other sources appeared to be a significant source of errors at short ranges for the 19 k bit/s system.

Note that a 19 k bit/s irreducible rate falls between an rms delay spread of 0.1 µs to 1 µs (Figure 18) for the single diversity systems and assuming $P_e = 10^{5}$.

Bussgang and his colleagues (1976) have considered these results in developing design criteria for a VHF tactical simulator for land mobile links. Considering Milulski's results, Bussgang notes that at 19 k bits/s, the multipath spread could become a substantial portion of the signaling element duration assuming the signaling rate equals the data rate, then a 10% spread would be 5.3 µs at 19 k bits/s.

Conventional FM carrier modulation techniques waste bandwidth. The packing ratio is reduced by an amount which depends on the modulation index used. Packing ratios are typically on the order of 0.1 bits/s/Hz. See Bello (1969b). The RF bandwidth occupied by the signal must at the same time be less than the coherent bandwidth of the channel to eliminate selective fading. Even in a flat fading channel most errors occur when the system is below FM threshold. Thus the use of digital modems on conventional FM carriers appears to be an inefficient way to transmit data.

The use of spread spectrum techniques also reduces the packing ratio (R/B < 0.01 bits/s/Hz) and suffers the same limitation of RF bandwidth where conventional reception is used as noted by Bello (1969b). However, if a RAKE type of receiver structure is used, the RF bandwidth no longer needs to be confined to be less than the correlation bandwidth.

When a system is dealing with many users rather than one, as in the land mobile service, the spread spectrum technique appears to have expanded capabilities over conventional modulation and spectrum accessing techniques. The number of simultaneous users in a cellular system using spread spectrum techniques far exceeds the number possible in an FM system. In addition to the high simultaneous usage rate the spectral efficiency is substantially improved. See Eckert and Kelly (1977). Spread spectrum carrier modulation appears to be useful in many other multiple access applications.

With more conventional systems when sufficient power is available, maximum data rates are achieved using a combination modulation scheme of multiple PSK and transmitting at different frequencies to increase the packing ratio as described in Section 9.

As an example, assume that a standard channel bandwidth of 50 kHz has been allocated for the FM carrier system where the packing ratio is typically 0.1 b/s/Hz for a modulation index of 3. The maximum expected rate in the allocated bandwidth is therefore 5.0 k b/s. However, if the link is dispersive and frequency selective at this rate, then a lower signaling rate must be used to avoid a high error rate caused by distortion. Thus the actual data rate may be considerably less than 5 k bits/s. Although no actual data are available, 1 k bits/s seems reasonable for suburban areas.

This can be compared with the data rates achievable with an m-PSK, n-FSK system designed to utilize fully the allocated bandwidth. For n=5 and m=8 the data rate is found to be 53 k b/s which is an order of magnitude better.

## 12. SUMMARY AND CONCLUSIONS

Communication system designers are faced with an ever-increasing demand for higher and higher data rates over radio channels. Systems utilizing such channels are adversely affected by frequency selective fading which perturbs the signal in unusual and ever-changing ways. At high rates this so-called "multiplicative noise" can be the primary source of errors rather than the omnipresent additive noise. This is because the unpredictable distortion, both amplitude and phase, and intersymbol interference caused by the channel ultimately limits the number of distinguishable characteristics of the signaling elements or symbols. Distortion thereby limits the rate at which a sequence of signals can be transmitted with an acceptable number of errors. In binary coded systems where only two symbol characteristics are changed (the minimum number required for transferring information), this signaling rate equals the data rate.

Even in an idealized system there are two physical limitations to the capacity of a communications channel—bandwidth and noise. These determine respectively the <u>signaling rate</u>, or number of symbols transmitted per unit time, and the <u>information content</u>, or number of information bits transmitted per symbol. Together, this rate and content determine information rate on a time basis.

Shannon's ideal capacity formula was used in Section 2 to define interrelationships between data rate, bandwidth, noise, and signal power for an idealized system. This relationship was plotted in a form different from the one commonly used. The curves for the idealized system show that the capacity is directly proportional to signaling power for a constant noise power spectral density and for a constant packing ratio--the data rate per unit bandwidth. Similar curves for certain practical systems operating over selective radio channels are given in Section 8, which show that the signaling rate or binary data rate is not directly proportional to signal power when signal distortion occurs in the channel. In fact, when distortion does occur, those rates are independent of the signal power. Most of the report discusses the causes for this distortion and its effect on the rates achievable with uncoded binary systems.

In summary, it is shown that the distortion (and intersymbol interference) is caused by the occurrence of multiple transmission paths between the transmitter and receiver terminals. This multipath exists because of scattering, reflecting and refracting mechanisms in the propagation medium. At high signaling rates, the multipath causes frequency-selective fading which distorts digitized signals. Even when individual paths are resolved, some distortion occurs due to medium dispersion and atmospheric turbulence. These individual paths however are extremely broadband.

The maximum undistorted signaling rate which can be achieved depends on the impulse response of the channel. The impulse response varies according to a number of factors including:

- operating frequency
- type of link and its geometry
- geographical location
- meteorological conditions
- antenna directivity and pointing angle.

Given the impulse response or its statistical representation, then the maximum achievable signaling rate depends on:

- user's reliability requirements or error rate
- type and level of diversity

- signal design
- modulation scheme

The maximum undistorted signaling rates have been given for a variety of links and for their responses. If this maximum rate is exceeded, then the information content of the signaling elements cannot be increased by conventional means. If this maximum signaling rate is not exceeded, then the information-carrying capacity of the channel can be increased by increasing the information content of each signaling element. This, however, may require complex implementation schemes and an excessive amount of power. Even for an idealized system, Shannon's capacity equation shows that it is extremely impractical to send more than 10 bits per cycle of available (allocated) bandwidth because of the power required. Since the available bandwidth of channels is limited to about 10% of the carrier frequency for technological reasons (Section 1), this means that the maximum achievable data rate for systems using the electromagnetic spectrum is about equal to the carrier frequency. Some typical rates in use today are compared with this limit in Figure 23. These are gross estimates and can vary widely depending on path length, transmitter power, antenna gain, reliability and system design.

The technologically limited region shown in Figure 23 assumes the bandwidth is 10% of the carrier frequency with an upper bound of 10 bits/s per unit of bandwidth and a lower bound of 1 bit/s per unit of bandwidth. The actual rates for typical systems fall well below these bounds because allocated bandwidths are not necessarily 10% of the carrier frequency or because of dispersive mechanisms in the channel. Also, maximizing the number of bits per hertz of bandwidth has not been an urgent consideration because bandwidth has been readily available particularly in the higher spectrum bands.

The principal conclusions reached from the results of this study and literature research program are

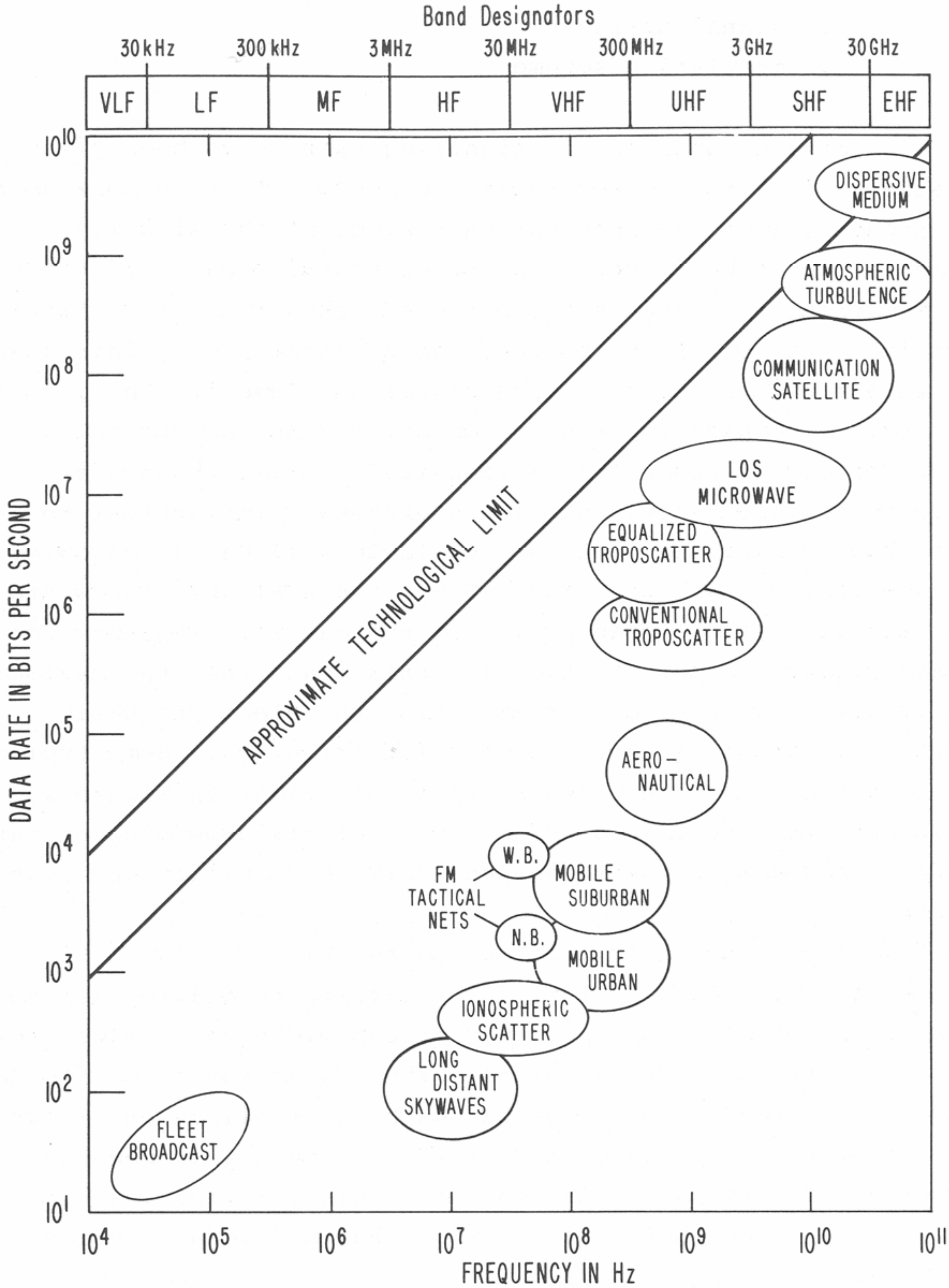


Figure 23. Data rate of typical systems compared with technological limits.

1. Dispersive mechanisms in a radio propagation channel can, at certain signaling rates, cause selective fading which distorts the signal and limits the maximum and minimum signaling rate. These limits cannot be overcome by increasing transmitter power. The maximum rate is limited by time dispersive mechanisms which cause frequency selective fading.
2. Where signaling rates are reduced so frequency selective fading does not limit performance, then the data rate can be increased by maximizing the number of information bits transmitted by each symbol.
3. Where channels are bandlimited by allocation or for technological reasons, the data rate can be increased by increasing the packing ratio. The maximum data rate per hertz of bandwidth should probably not exceed 10 bits/s/Hz due to the excessive power required.
4. The impact of frequency selectivity on a channel is a function of the response of the channel, the signal design, and the rate of change of that signal. Channel responses depend upon the link being used and the propagation conditions for that link.
5. The response in the time domain, i.e., the impulse response of a channel is a measure of the transmission capabilities for that channel. Statistical representations of the responses of several channels for a given type of link can be used to determine system performance over that link.
6. The measured response for mobile links indicate maximum signaling rates may vary from $10^3$ symbols per second to $10^6$ symbols per second depending on the environment, the modulation scheme, level of diversity and the acceptable error rate. Some frequency effects may also occur due to varia-

tions in the reflection coefficients with frequency and due to the attenuation of trees and foliage at high frequencies.

7. The maximum achievable data rate over a channel with a fixed signaling rate depends on the allocated bandwidth and transmitter power. For a mobile link with a 50 kHz allocated bandwidth and using quadrature PSK in conjunction with multiple frequency shift keying, the maximum data rate was estimated to be 43 k bits/s in suburban areas, and 7.6 k bits/s in urban areas. Estimates for military tactical nets using FM carrier modulation were about 1 k bits/s for the urban area.

8. Since the signals arriving via individual paths in a multipath channel are extremely broadband, it appears feasible to structure a system which combines each path coherently and thereby takes advantage of this broadband feature. This adaptive equalization process greatly increases transmission capability but requires that the path characteristics change relatively slowly compared to other system response times.

9. Preliminary impulse response measurements at 8.6 GHz using high resolution equipment indicate a considerable difference in the delay profiles from those obtained at lower frequencies. This is attributed to a lessening of the effects of diffraction around obstructing objects, the variation in attenuation caused by smaller objects such as leaves on trees, and differences in the reflection coefficient of reflecting objects.

# 13. A RECOMMENDATION

The signaling and data rates for various links and channel responses estimated in this report are based on certain assumptions and a limited amount of data. One's confidence in these estimates would be greatly enhanced if comparisons could be made with actual performance data. Unfortunately, such data are severely lacking. Several workers have measured responses on radio channels and others have measured the error rates of specific systems over radio channels. Seldom, however, have both response and performance been measured simultaneously and at rates where selective fading occurs, in spite of the fact that both measurement techniques are well established.

For some types of links in the future, some people expect a more stringent channelization of spectrum bandwidth as filter technology advances. See Cuccia (1976). This coupled with the increasing demand for higher data rates, implies a need for signal designs and modulation techniques that maximize the number of bits that can be transmitted on a per-unit-of-bandwidth basis. For other types of links, less channelization may be better. Multiple access systems for example. Spread spectrum system technology could provide substantial improvement over conventional (FM) modulation and accessing techniques for the land mobile services. See Eckhert & Kelly (1977).

Designers of such systems will need a comprehensive data base to characterize the channel and its effect on various signals. As time goes on, it becomes more and more difficult to obtain this data base because it requires broadband measurements over clear channels. Already portions of the spectrum are overcrowded with users making it difficult to make broadband impulse measurements and wide band performance measurements without encountering man-made interference. This is particularly true in the mobile area where already the lower bands are filled with users in every city. Nielson (1975), for example, was unable to measure the impulse response in the 400 MHz land mobile band because of the intense interference which existed in the San Francisco Bay Area.

Because a firm data base is so essential to the design of advanced systems making maximum utilization of the limited spectrum, it is recommended that measurement programs be instituted to characterize various channels (at frequencies and locales that are still clear) as soon as possible. This program should include both additive noise and response data (either in the frequency domain or the time domain) over a variety of links and channels. Impulse response measurements should use the highest practical resolution.

Continuous recordings of the response and the noise should, after processing, be capable of providing appropriate measures of the time and frequency dispersiveness of the channel and a statistical representation of the noise.

At the same time, the error performance of a system should be measured at various keying rates and using a convenient modulation scheme such as quadrature PSK so that performance predictions can be verified.

Throughout this report, the additive noise has been assumed to be white with a constant noise power spectral density. This of course is often not the case and particularly not true for the mobile environment where the primary error-causing additive noise is more likely to be man-made (either ignition or power-line noise) with impulsive properties or interference from adjacent channels. Measurement programs which are designed to characterize the channel should include additive-noise measurements commensurate with the response and performance measurements, and, an attempt should be made to resolve the error-causing effects.

An accurate wideband characterization of the multiplicative and additive noise in the radio channel is essential to the future development of advanced communication systems. Statistical models based on experimental data are also useful for simulation experiments in order to avoid costly hardware tests of ad hoc systems. An example of this latter application is given by Suzuki (1977) who utilized experimental data to establish a statistical model for the urban radio propagation medium.

## 14. ACKNOWLEDGMENTS

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The amount of information that can be transferred over any communications link in a unit of time depends upon a number of factors--both technological and physical. This report discusses these factors with emphasis on the fundamental physical limitations of radio channels. The maximum rate of information transfer over a number of radio communication links is derived and compared with an idealized system. The results obtained show that at certain signaling rates, dispersion in the channel, caused by multipath, limits the number of permissible signaling characteristics that can be changed. This may occur even when only two characteristics are used--the minimum number required for information transfer. Thus, dispersive propagation mechanisms limit a binary channel's capacity, and unlike additive noise, this limit cannot be overcome by increasing the signal power.


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